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# SEA LEVEL CHANGES ON THE FINNISH COAST AND THEIR RELATIONSHIP TO ATMOSPHERIC FACTORS

Milla M. Johansson

Department of Physics
Faculty of Science
University of Helsinki
Helsinki, Finland

ACADEMIC DISSERTATION in geophysics

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Title
Sea level changes on the Finnish coast and their relationship to atmospheric factors

Abstract

Changes in sea level behaviour on the Finnish coast of the Baltic Sea were studied, based on observations from the early 20th century to the present. The relationship of sea level changes to changes in atmospheric factors – geostrophic wind and air pressure – was also studied.

Wind and air pressure are the main factors affecting the short-term behaviour of sea level in the Baltic Sea. Monthly mean sea levels on the Finnish coast correlate with the monthly mean zonal geostrophic wind over the Baltic Sea. The correlation explains 82–88% of the inter-annual sea level variability, and 76–81% of the intra-annual month-to-month variability. The supposed mechanism behind this involves changes in the total water volume of the Baltic Sea due to water transport through the Danish Straits, as well as the internal redistribution of water volume in the Baltic Sea basin; both processes are controlled by atmospheric factors.

The seasonal sea level behaviour on the Finnish coast has changed during recent decades. In 1970–1989 sea levels were higher than previously in November–December, while in 1990–2009 sea levels were higher than previously in January–March. The observed annual sea level maxima have increased by 15–30 cm from the 1930s to the present. The probabilities of other higher sea levels, those exceeded a few weeks/year or less, have also increased. The increase is most evident in wintertime (January–March). Part of the observed changes is related to changes in monthly mean atmospheric conditions.

Mean sea levels on the Finnish coast had a declining net (apparent) trend of 1.0–7.2 mm/yr during the 20th century, mainly due to postglacial land uplift, which was partly balanced by the external large-scale sea level rise, and by an increase in the zonal wind. The large-scale sea level rise due to ocean density and circulation changes, as well as to the melting of land-based ice sheets, glaciers and ice caps, had a global average rate of 1.7 mm/yr, but the local contribution is at present uncertain. The zonal wind contributed an increasing trend of 0.5–1.2 mm/yr in sea levels on the Finnish coast. Since the 1980s, the mean sea level trends have accelerated, i.e. the decline has slowed. In the 1980s–1990s, this was due to changes in regional wind conditions. Since the 1990s, the trends still show an acceleration that is not related to regional wind conditions.

A synthesis of published global sea level scenarios, and geostrophic wind scenarios from nine global circulation models, were utilized to estimate future sea level changes. On average, the changes in wind conditions will result in 6–7 cm higher sea levels on the Finnish coast by the end of this century compared to those in the present climate. The large-scale sea level rise would alone contribute 24–126 cm of sea level rise on the Finnish coast over the period 2000–2100. These changes were combined with a 41–99 cm decline due to land uplift. The accelerated sea level rise is expected to be stronger than land uplift in the Gulf of Finland, where rising relative sea levels will result. In the Gulf of Bothnia, the stronger land uplift will still balance the sea level rise, according to the average scenario. The uncertainties are large, and high-end scenarios project rising sea levels everywhere on the Finnish coast.

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Nimeke

Suomen rannikon vedenkorkeusmuutokset ja niiden yhteys sääoloihin

Tiivistelmä

Meriveden korkeutta on säännöllisesti mitattu Suomen rannikolla 1800-luvun puolestavälistä alkaen. Tässä työssä tarkastellaan vedenkorkeuden käyttäytymisessä havaittuja muutoksia sekä tuuli- ja ilmanpaineolojen vaikutusta niihin.

Tuuli ja ilmapaine ovat tärkeimmät Itämeren vedenkorkeusvaihteluita säätelevät tekijät. Työssä osoitettiin että n. 80 % Suomen rannikon vedenkorkeuden kuukausikeskiarvojen vaihtelusta liittyy tuuli- ja ilmanpaineoloihin. Taustalla vaikuttaa pääasiassa kaksi mekanismia. Tuulet ja ilmanpainevaihtelut painavat vettä Tanskan salmien kautta Pohjanmereltä Itämerelle ja muuttavat näin Itämeren kokonaisvesimäärää. Ne myös kallistavat vedenpintaa Itämeren eri osien välillä.

Vedenkorkeuden vuodenaikaiskäyttäytyminen on muuttunut viime vuosikymmeninä. Vuosina 1970–1989 marras-joulukuun vedenkorkeudet olivat keskimäärin korkeampia kuin vuosisadan alkupuolella. Toisaalta vuosina 1990–2009 tammi-maaliskuun vedenkorkeudet olivat keskimäärin aiempaa korkeampia. Korkeat vedenkorkeudet ovat kasvaneet erityisesti talviaikaan, tammi-maaliskuussa, sitä enemmän mitä harvinaisemmista arvoista on kyse. Vuosittain mitatut maksimivedenkorkeudet ovat kasvaneet 15–30 cm 1930-luvulta nykypäivään. Osa näistä muutoksista liittyy länsituulisuuden muutoksiin Itämeren alueella.

Keskimääräinen vedenkorkeus laski Suomen rannikolla maan suhteen 10–72 cm 1900-luvun aikana. Lasku johtui pääasiassa jääkauden jälkeisestä maankohoamisesta, jonka nopeus vaihtelee eri osissa rannikkoa. Maankohoamisen vaikutusta hidasti maailmanlaajuinen merenpinnan nousu, joka aiheutuu mm. valtamerien lämpölaajenemisesta sekä mannerjäätiköiden ja pienempien jäätiköiden sulamisesta. Valtamerien pinta nousi keskimäärin 17 cm 1900-luvulla, mutta paikallinen vaikutus Itämerellä ei ole tarkkaan tiedossa. Länsituulten voimistuminen nosti vedenkorkeutta Suomen rannikolla 5–12 cm, vaikkakaan nousu ei ole ollut tasaista vaan muutoksen suunta on vaihdellut vuosikymmenestä toiseen.

Skenaariot keskimääräiselle vedenkorkeudelle vuodelle 2100 laskettiin yhdistelmänä kirjallisuudessa julkaistuista valtameren pinnannousun skenaarioista, tuuliolojen vaikutuksesta ilmastomallien pohjalta, sekä maankohoamisesta. Tuuliolojen muutokset johtavat keskimäärin 6–7 cm nykyistä korkeampiin vedenkorkeuksiin Suomen rannikolla. Maailmanlaajuinen merenpinnan nousu nostaa Suomen rannikon vedenkorkeuksia 24–126 cm. Maankohoaminen puolestaan aiheuttaa 41–99 cm laskun. Suomenlahdella kiihtyvän merenpinnan nousun odotetaan olevan maankohoamista voimakkaampaa, ja vedenkorkeus rannikoilla tulisi siis nousemaan. Pohjanlahdella voimakkaampi maankohoaminen riittää vielä voittamaan keskiskenaarion mukaisen merenpinnan nousun. Skenaarioissa on kuitenkin isoja epävarmuuksia, ja korkeimmat skenaariot ennustavatkin keskimääräisen vedenkorkeuden nousua kaikkialla Suomen rannikolla.

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## Preface

The sea has always fascinated me. Childhood summer visits to the Finnish archipelago, followed by sailing trips in the Baltic Sea with traditional wooden sailing ships, stimulated in me an interest towards that vast, mysterious, unpredictable and powerful element.

Thus, getting a summer job in the Finnish Institute of Marine Research (FIMR) in 1998 was a dream fulfilled. I want to express my thanks to Prof. Jouko Launiainen, the head of the Department of Physical Oceanography, for employing me and providing me opportunities for the sea level research, as well as taking me to my first field expeditions in the Baltic Sea, the Greenland Sea and further down to the Weddell Sea in Antarctica.

Sea level research has been part of my career from the beginning. I thank Prof. Kimmo Kahma, my supervisor first at FIMR and later at the Finnish Meteorological Institute (FMI), for his expertise and continuous and enthusiastic support during all these years when I have strived to achieve deeper understanding on the complicated phenomenon of sea level variability.

Considering data availability, sea levels were a good subject to study. I was provided with high-quality time series commencing from the late 19$^{th}$ century. First thanks for those data go to all the people who have contributed during the past decades, most of whom I never met: taking care of the mareographs, decoding the data from the paper records, and so on. I also want to thank Hanna Boman and Stina Visa, who have diligently ensured the quality of the datasets up to finest detail.

I owe thanks to my co-authors for their valuable work, support and fruitful discussions when preparing the papers for this thesis. Without the contributions of Hanna Boman, Kimmo Kahma, Jouko Launiainen, Hilkka Pellikka and Kimmo Ruosteenoja, this thesis would never have seen the daylight. I also thank the pre-examiners, Prof. Pentti Mälkki and Dr. Kai Myrberg, whose valuable comments greatly improved the summary of this thesis. I thank Prof. Matti Leppäranta, my supervisor, whose lectures on “Principles of oceanography” in mid-1990s first made me aware of such a fascinating branch of science. Special thanks go to Dr. Heidi Pettersson, the head of our research group at FMI, who gently encouraged me to finish my thesis even when my own faith on the project was not at its strongest.

I thank all my colleagues at FIMR and FMI for countless interesting discussions on diverse aspects of life, good atmosphere at the workplace, and support even during the cloudier days. It has been a joy to work with people who share the enthusiasm on marine science.

My research career has involved not just the sea level variations on the coastline, but also open seas, and even some water in its solid form. This diversity has ensured that the work has always retained its fascination. I have especially enjoyed the field expeditions – be that at sea, on sea ice or on the continental glaciers. Thus, I want to express my final special thanks to Drs. Timo Vihma and Roberta Pirazzini, who provided me an opportunity to see the Antarctic continent on two research expeditions.

On board RV Aranda, Baltic Sea, April 2014 Milla Johansson

CONTENTS

## LIST OF ORIGINAL PUBLICATIONS

I *Johansson, M., Boman, H., Kahma, K.K. and Launiainen, J.,* 2001. Trends in sea level variability in the Baltic Sea. *Boreal Environ. Res. 6,* p. 159–179.

II *Johansson, M.M., Kahma, K.K. and Boman, H.,* 2003. An Improved Estimate for the Long-Term Mean Sea Level on the Finnish Coast. *Geophysica 39:1–2,* p. 51–73.

III *Johansson, M.M., Kahma, K.K., Boman, H. and Launiainen, J.,* 2004. Scenarios for sea level on the Finnish coast. *Boreal Environ. Res. 9,* p. 153–166.

IV *Johansson, M.M., Pellikka, H., Kahma, K.K. and Ruosteenoja, K.,* 2014. Global sea level rise scenarios adapted to the Finnish coast. *J. Marine Syst. 129,* p. 35-46.

The author did most of the analyses in Paper I and participated in its writing under the guidance of the other authors. The author was responsible for the analyses in Papers II and III and wrote most of the papers under the guidance of the other authors. In Paper IV the author was responsible for the analyses of the meteorological forcing and the local scenarios on the Finnish coast and also wrote most of the paper. She also supervised the second author in making the analyses and writing the parts concerning the large-scale sea level rise. The author is solely responsible for the summary of this thesis.

# 1 INTRODUCTION

Sea levels are relevant for human activities in several respects. Extreme floods are a threat to coastal facilities. The extent of sea level variations affects navigation in coastal areas and harbours. Changes in sea level behaviour may affect coastal ecosystems. Sea level is also one of the indicators of climate change, as it responds to both global-scale warming and changes in local atmospheric conditions. The current interest in climate change and awareness of the need to prepare for its effects have led to increasing interest in such questions as: How much and how fast can the sea level rise? How high floods should we be prepared for? Will they be higher than before? These questions are asked, for instance, by people responsible for the planning and construction of coastal infrastructure. To be able to project the future, an understanding of past sea level changes and the underlying mechanisms is needed.

The semi-enclosed intra-continental Baltic Sea exhibits its own sea level behaviour, which differs from that of the larger oceans. Sea level variations in the Baltic Sea have been extensively studied, resulting in a good knowledge of the underlying mechanisms. Ekman (2010) presents a detailed overview of the historical observations and studies from the 17$^{th}$ century onwards, including some early remarks on the role of wind and air pressure affecting sea level variations (Lagerlöf, 1698; Gissler, 1746; Colding, 1881). In the 20$^{th}$ century, Witting (1918), Hela (1944), Lisitzin (1974) and Ekman (2010), among others, have published extensive analyses of Baltic sea levels. Many of the more recent studies have focused on the long-term changes and the potential effect of climate change on sea level behaviour (BACC author team, 2008; Dailidienė *et al.*, 2006; Suursaar and Sooäär, 2007; Suursaar *et al.*, 2006; Ekman, 2010; Hünicke and Zorita, 2006; among others).

These studies were facilitated by the Baltic sea level measurement series, which are among the longest in the world. The first records of floods were begun in 1703 in St. Petersburg in the eastern Gulf of Finland (Averkiev and Klevannyy, 2010; Leppäranta and Myrberg, 2009), while the longest continuous sea level time series commenced in 1774 in Stockholm (Ekman, 2010). On the Finnish coast, regular sea level measurements date back to the late 19$^{th}$ century (Renqvist, 1931). Since the 1990s, satellite altimeter data on Baltic sea levels have complemented tide gauge data, although near-coastal applications in the Baltic Sea require more specialized data treatment than do the open oceans (e.g. Madsen *et al.*, 2007).

This study targets sea level processes and changes on the Finnish coast of the Baltic Sea. As time passes, longer and longer time series of sea level observations are accumulating, and as the effects of the global climate change are becoming more and more evident around us, it is worth analyzing to what extent they are reflected in sea level variations. This work was also motivated by the practical needs of Finnish society, which naturally determined the focus on the Finnish coast.

Atmospheric processes, particularly variations in air pressure and wind conditions, have a large effect on sea level variations in the Baltic Sea. One aim of this study is to statistically quantify the relationship between these factors and sea level. This serves as a tool in analyzing the potential role of changes in atmospheric conditions behind the observed changes in local sea level behaviour.

The objectives of this study are, considering sea levels on the Finnish coast:

1) To construct a simple statistical relationship to quantify the effects of wind and air pressure on monthly mean sea level variations.
2) To analyze the observed changes in short-term sea level variability since the early 20$^{th}$ century, on time scales ranging from seasonal variations to extreme sea level events.
3) To investigate whether the observed changes found in 2) are related to changes in atmospheric factors, using the statistical relationship established in 1).
4) To calculate the long-term trends in mean sea level since the early 20$^{th}$ century, and to analyze whether these trends have changed, reflecting the observed changes in the rate of the large-scale sea level rise in the oceans.
5) To construct mean sea level scenarios for the 21$^{st}$ century, taking into account the relevant processes, including atmospheric factors.

This summary is based on and extends the results from four papers (I–IV), in which sea levels on the Finnish coast were studied. Paper I was a detailed analysis of observed changes in short-term (mainly intra-annual) sea level variability, including studies of extreme values, standard deviations, probability distributions and spectra. Significant changes in several aspects of sea level behaviour were found during the 20$^{th}$ century, for instance an increase in sea level maxima and the probabilities of high sea levels. The correlation between the sea levels and the North Atlantic Oscillation (NAO) index was briefly analyzed.

In Paper II, the long-term (inter-annual and decadal) changes in the mean sea level and their relation to the NAO index were studied. In Paper III, the results of Paper II were extended into the future by constructing sea level scenarios for the 21$^{st}$ century. The scenarios were based on the global sea level scenarios of the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC; Church *et al.*, 2001), as well as on the calculated local land uplift rates and an estimate for the changes related to atmospheric factors based on climate model scenarios for the NAO index.

In Paper IV, the investigations were refined by showing that the zonal geostrophic wind exhibits a stronger correlation with local sea levels than does the NAO index, providing a better estimate for the effect of the atmospheric factors. The mean sea level scenarios were updated. The TAR scenarios were now replaced by a broader synthesis, in which global sea level rise scenarios from various sources, as well as the uneven geographical distribution of the global sea level rise, were taken into account.

This summary begins with an overview of the general properties of the Baltic Sea and the local sea level behaviour (Section 2), and a presentation of the Finnish sea level observations (Section 3). The methods used are then described (Section 4). The relationship between atmospheric factors and sea level is studied by extending the analyses of Paper IV (Section 5). The analyses of Paper I on short-term variability are extended, and their relationship to atmospheric changes is studied (Section 6). The past mean sea level trends are analyzed by extending the studies of Papers II–IV (Section 7). The sea level scenarios, which were an essential part of Papers III and IV, are briefly summarized (Section 7.4). Finally, the main conclusions are presented (Section 8).

# 2 Baltic sea level behaviour

## 2.1 General features of the Baltic Sea

The Baltic Sea is a semi-enclosed intra-continental sea connected via the North Sea to the North Atlantic Ocean (Fig. 2.1). The average depth of the Baltic Sea is 54 m, the deepest point in the Landsort Deep being 459 m. The surface area is 393 000 $km^2$ and water volume 21 200 $km^3$ (Leppäranta and Myrberg, 2009).

The Baltic Sea consists of several sub-basins with different bottom topography, orientation and coastline character. The Finnish coast is delimited by the east-west oriented Gulf of Finland, and the south-northeast oriented Gulf of Bothnia, which can be further divided into the Bothnian Sea and the Bothnian Bay. The Archipelago Sea, characterized by thousands of islands of varying sizes, separates the Bothnian Sea from the Baltic Proper.

The narrow and shallow Danish Straits (Fig. 2.2), and beyond them the sounds of the Kattegat and Skagerrak, connect the Baltic Sea to the North Sea. The Danish Straits, with depths of mostly less than 20 m, considerably limit water transport between the Baltic Sea and the North Sea. The renewal time of the entire water mass of the Baltic Sea is 50 years. The water transport through the straits is presented in more detail in Section 2.3.

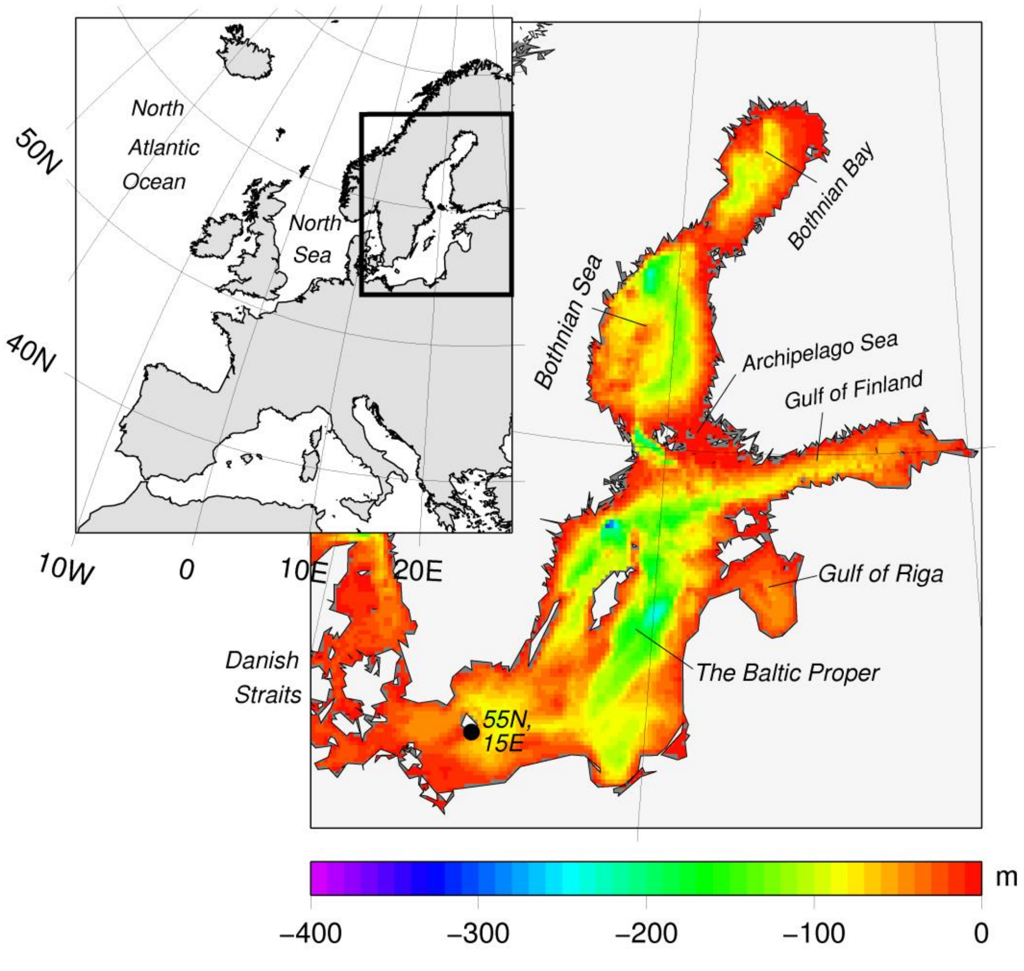



FIGURE 2.1. Bottom topography and sub-basins of the Baltic Sea (topography from Seifert *et al.*, 2001).

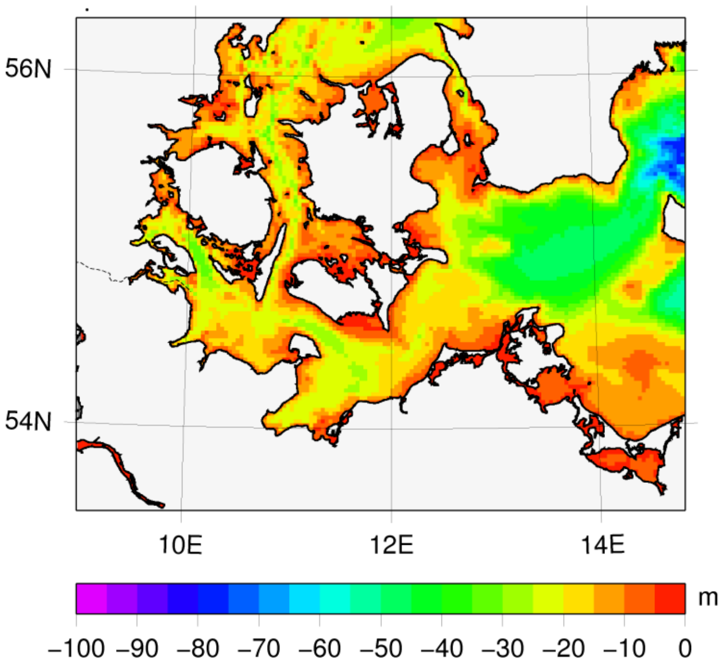



FIGURE 2.2. Bottom topography of the Danish Straits connecting the Baltic Sea to the Kattegat and the North Sea (Seifert *et al.*, 2001).

The Baltic Sea is a brackish water body with an average salinity of 7‰, considerably lower than the typical ocean salinity of 35‰. Inside the Baltic Sea the salinity varies, decreasing from 25‰ in the Danish Straits to zero in river mouths. This salinity gradient is due to the opposing effects of incoming saline water from the North Sea and freshwater runoff from the rivers.

The Baltic Sea is seasonally ice-covered in wintertime, the length of the ice season being 5–7 months. The annual maximum extent of the ice cover varies from 12.5% during extremely mild winters (ice cover only in the Bothnian Bay and eastern Gulf of Finland) to 100% during extremely severe winters, being 45% on average (Leppäranta and Myrberg, 2009).

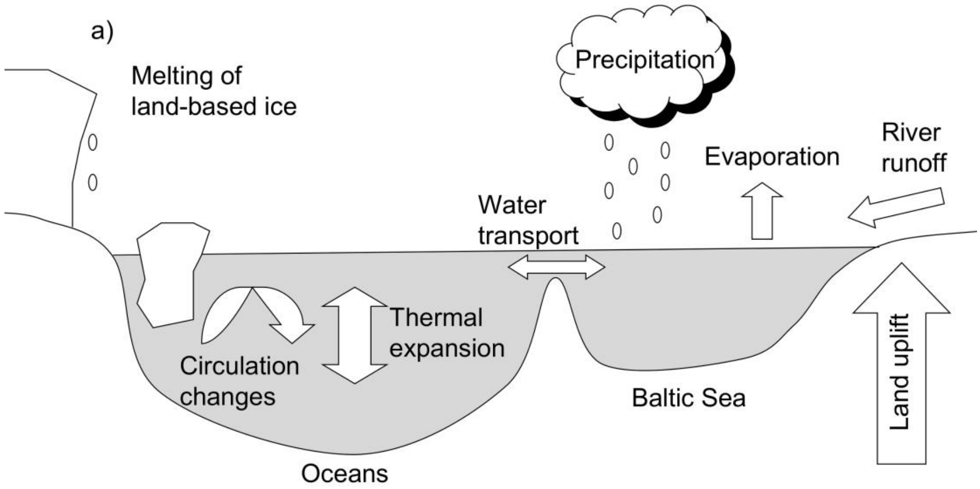
## 2.2 CHARACTERISTICS OF SEA LEVEL VARIATIONS

The semi-enclosed nature of the Baltic Sea characterizes the local sea level behaviour. On the one hand, being connected to the World Ocean, the Baltic Sea experiences its share of effects originating from outside, such as the sea level rise due to the melting of continental ice sheets in a warming climate. On the other hand, as a small, irregularly-shaped basin, the Baltic Sea exhibits its own local sea level behaviour which is strongly dependent on regional atmospheric phenomena.

The main factors affecting the Baltic sea level are given in Table 2.1 and presented in Fig. 2.3. These factors can be divided into processes that alter the total water amount in the Baltic Sea basin: water exchange through the Danish Straits, river runoff, precipitation and evaporation, and, on the other hand, processes that primarily redistribute water masses inside the basin: wind conditions, air pressure variations, and seiche, as well as some other processes. Other, slightly different classifications for the internal and external processes affecting sea level variations have been presented e.g. by Hela (1944) and Lisitzin (1974). According to Samuelsson and Stigebrandt (1996), external forcing, which they consider to consist of the water exchange and freshwater supply, explains 50–80% of the total sea level variance in the Baltic Sea. Considering this work, it is noteworthy that the effect of atmospheric factors on Baltic sea levels is a combination of both: processes altering the water amount and acting on time scales of from weeks to decades, and processes redistributing water inside the basin, which mainly act on time scales shorter than a week (Table 2.1).

TABLE 2.1. An overview of factors contributing to sea level variations in the Baltic Sea.

| Factor | Mechanism | Time scale | Scale of variability on the Finnish coast |
|---|---|---|---|
| Postglacial land uplift | declining long-term trend due to upward crustal motion | centuries | 4–10 mm/yr (Paper IV) |
| Large-scale sea level rise | rising sea level due to ocean density and circulation changes, melting of land-based ice and other large-scale phenomena | from decades to centuries | global average 1.7 mm/yr in 1900–2009 (Church and White, 2011) |
| Baltic Sea water volume | changes in total water amount by transport through the Danish Straits; river runoff, precipitation and evaporation are minor contributors | from one week to decades | water storage capacity 500 $km^3$ (Leppäranta and Myrberg, 2009), corresponding to 1.3 m of sea level variability |
| | density changes due to changes in temperature and salinity | from weeks to decades | sea level changes due to annual mean variations of salinity ± 2 cm in the Gulf of Finland (Vermeer *et al.*, 1988); seasonal thermal expansion a few cm:s |
| Wind-induced internal water redistribution | transport of water between sub-basins, piling-up against coastlines | from hours to weeks | several tens of cm:s (e.g. Hela, 1948) |
| Air pressure induced internal variations | inverse barometer effect: sea level rises under low air pressure conditions | from hours to weeks | several tens of cm:s, theoretical ratio 1 cm/hPa (Defant, 1961a) |
| Internal oscillation (seiche) | water oscillates back and forth between sub-basins; oscillation initiated by wind or air pressure variations | 27–39 hour periods (Lisitzin, 1974) | tens of cm:s |
| Ice cover | attenuates the piling-up effect of wind | from hours to weeks | some tens of cm:s (Lisitzin, 1957) |
| Astronomical tide | periodical oscillations induced by the gravitation of Moon and Sun | periods from 12 hours to 18.6 years | less than 10 cm (Witting, 1911; Lisitzin, 1974) |



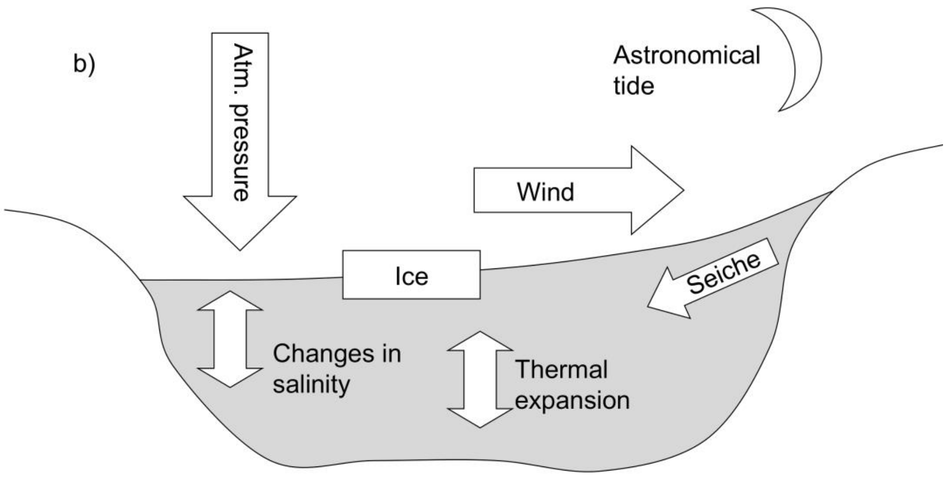




FIGURE 2.3. The processes inducing sea level variations in the Baltic Sea: a) processes changing the total water amount and b) processes primarily redistributing water inside the basin.

## 2.3 CHANGES IN WATER AMOUNT

The mean annual inflow and outflow of water through the Danish Straits amount to 1180 and 1660 km$^3$, respectively, the difference comprising the 480 km$^3$ net freshwater input from rivers and precipitation minus evaporation. Instantaneous flows on shorter time scales can markedly deviate from this average pattern: instantaneous flows of up to 25 km$^3$/day occur in both directions (Leppäranta and Myrberg, 2009).

The contribution of atmospheric factors to water transport through the straits is visualized in Fig. 2.4. Water transport is predominantly driven by a sea level difference between the Baltic Sea and the North Sea. In inducing such a sea level gradient, atmospheric factors play an important role. Westerly winds, for instance, move water from the North Sea towards the straits, and at the same time drive water away from the southwestern corner of the Baltic Sea, lowering the sea level next to the straits. Such a configuration results in a sea level gradient that favours the inflow of water. Air pressure variations over the North Sea alter the sea level outside the straits, and pressure gradients over the Baltic Sea redistribute water, the resulting gradient driving water through the straits. The changing water volume of the Baltic Sea – resulting from the water exchange or the freshwater budget – also alters the gradient.

The efficiency of water transport through the Danish Straits is substantially limited by the transport capacity of the narrow and shallow straits. An instantaneous flow of 25 $km^3$/day corresponds to a sea level change of 6 cm/day over the entire Baltic Sea. Thus, the observed changes of several tens of centimetres in the Baltic Sea average level – i.e. hundreds of $km^3$ in the water volume – take more than a week to occur, even in ideal conditions. Accordingly, sea level variations with time scales shorter than a week practically experience the Baltic Sea as a closed basin, while variations with time scales longer than a month penetrate the straits, establishing open-basin behaviour (e.g. Samuelsson and Stigebrandt, 1996; Ekman, 2010).

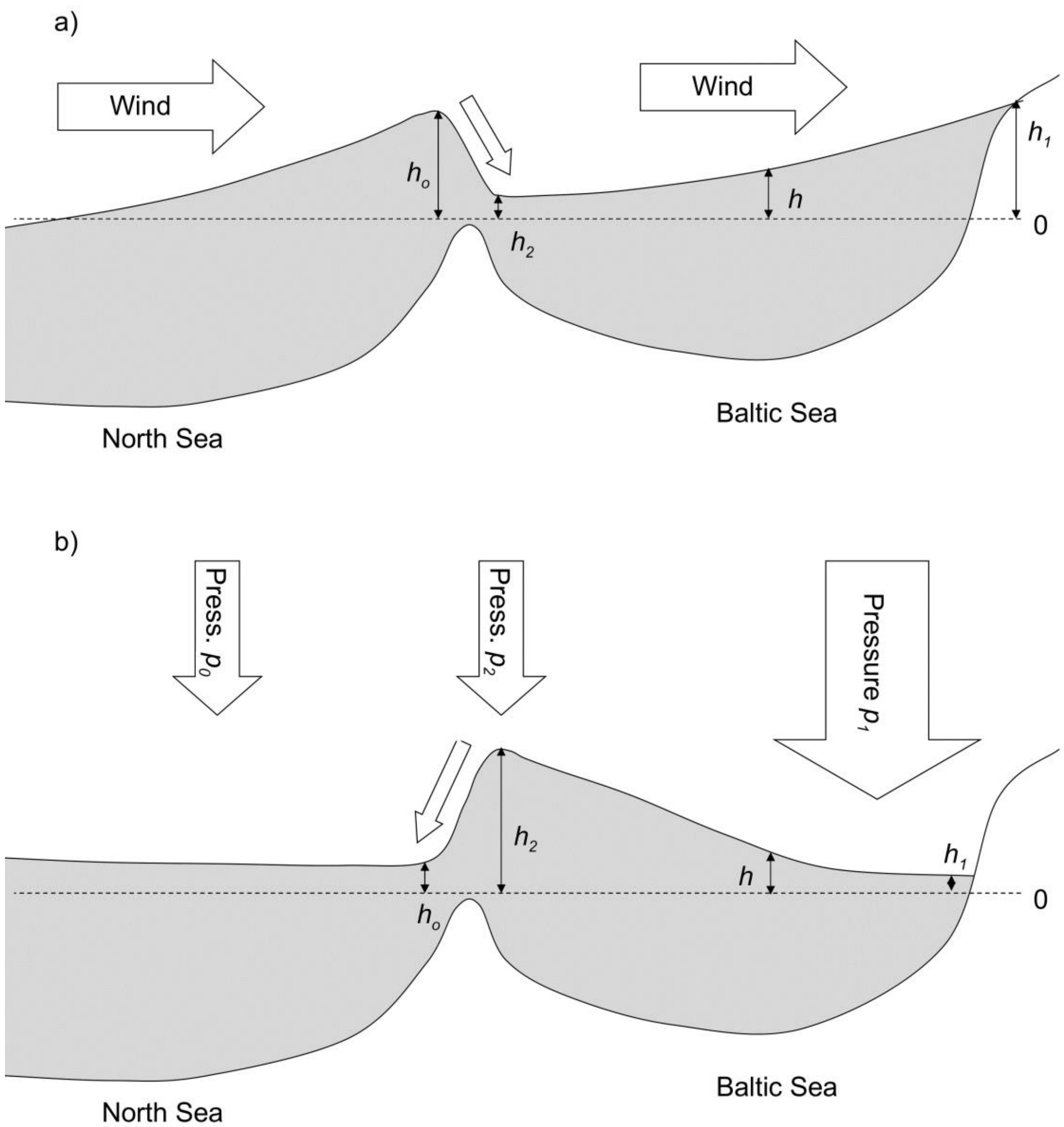



FIGURE 2.4. Schematic representation of water transport through the Danish Straits induced by a) wind, water flowing down the sea level gradient $h_o - h_2$, and b) air pressure, water flowing down the hydrostatic pressure gradient $(p_o + \rho g h_o) - (p_2 + \rho g h_2)$ in the narrow and shallow straits between the Baltic Sea and the North Sea (Kattegat).

The mean annual river runoff to the Baltic Sea amounts to 440 km$^3$, while a maximal monthly runoff of 87 km$^3$ has been recorded (Leppäranta and Myrberg, 2009), corresponding to a sea level increase of 22 cm. The mean annual precipitation amounts to 215 km$^3$ and evaporation to 175 km$^3$, their net effect corresponding to a sea level increase of 10 cm. The effect of this freshwater budget on the water volume changes of the Baltic Sea is thus minor compared to the water transport through the Danish Straits.

The Danish Straits also convey into the Baltic Sea the global large-scale sea level rise, which results from ocean density and circulation changes and the melting of land-based ice sheets, glaciers and ice caps in a warming climate. The global average rate for this sea level rise was 1.7 ± 0.2 mm/yr in 1900–2009, and since 1961, 1.9 ± 0.4 mm/yr (Church and White, 2011). During recent decades, satellite altimeter measurements of the world oceans show higher rates, such as 3.1 mm/yr in 1993–2003 (Bindoff *et al.*, 2007), 3.3 mm/yr in 1993–2007 (Cazenave and Llovel, 2010), 3.2 ± 0.4 mm/yr in 1993–2009 (Church and White, 2011), or 3.4 ± 0.4 mm/yr in 1993–2009 (Nerem *et al.*, 2010). The global-coverage altimeter measurements also reveal considerable regional variability in the rates of sea level change, mainly due to nonuniform changes in ocean thermal expansion (Cazenave and Llovel, 2010).

## 2.4 Redistribution of water due to atmospheric factors

Besides driving the water transport through the Danish Straits, wind stress and air pressure variations contribute to the internal water redistribution among the Baltic Sea sub-basins.

Wind stress drives water from one part of the Baltic Sea to another. Southwesterly winds, for instance, force water into the northeastern parts of the sea. Changing weather patterns redistribute water over periods of hours and days. Wind stress also piles water against coastlines on time scales varying from days down to less than an hour, with local storm surges in small bays and at coastal sites. The amplitude of the piling-up effect increases towards the closed ends of the bays, reaching several tens of centimetres at the ends of the Finnish coast (e.g. Hela, 1948; Lisitzin, 1974), even more in the innermost part of the Gulf of Finland at St. Petersburg (Averkiev and Klevannyy, 2010). The effect of wind stress is reduced by a high concentration ice cover (Lisitzin, 1957; Omstedt and Nyberg, 1991).

Air pressure variations affect sea levels by the inverse barometer effect: theoretically, a pressure increase of 1 hPa corresponds to a sea level decrease of 1 cm (Defant, 1961a). In practice, as the Danish Straits limit the changes in the total water volume of the Baltic Sea, on short time-scales it is the air pressure differences between different parts of the Baltic Sea that are the most important. Local air pressure variations affect sea levels over durations of hours to days. Local meteotsunamis connected with thunderstorm fronts may cause rapid sea level fluctuations in less than one hour (Renqvist, 1926).

The sea level gradients induced by wind and air pressure variations can result in attenuating back-and-forth oscillations between the sub-basins of the Baltic Sea, the so-called seiche (Witting, 1911; Neumann, 1941; Lisitzin, 1959, 1974; Wübber and Krauss, 1979). When wind stress has piled up water into the Gulf of Finland, for instance, and this stress ceases, the sea level gradient drives water back into the Baltic Proper. This results in an opposite sea level gradient which results in a water oscillation back into the Gulf of Finland. Several cycles of this kind of back-and-forth oscillation can result.

The period of seiches between the Gulf of Finland and the Baltic Proper is about 26–27 hours, and between the Gulf of Bothnia and the Baltic Proper about 39 hours

(Lisitzin, 1974). The amplitude of a seiche can reach tens of centimetres in the inner parts of the sub-basins, while in the middle part of the area, near the nodal point of the oscillation, the effect on the sea level is minor. This, together with the wind-induced piling-up which is strongest at the closed ends of the bays, results in the most extreme sea levels being observed in the eastern Gulf of Finland, southwestern Baltic Sea, Gulf of Riga, and northern Bothnian Bay (for an overview of the extremes measured in different parts of the Baltic Sea, see Fig. 1 of Averkiev and Klevannyy, 2010).

### 2.5 Other factors: density changes, tides and land uplift

Changes in salinity and temperature affect water density and volume. The permanent salinity gradient between the North Sea and the inner Gulf of Bothnia corresponds to a 35–40 cm permanent sea level gradient (Witting, 1918; Ekman and Mäkinen, 1996). Temporal variations in local salinity, on the other hand, only induce minor variations in sea level. Vermeer *et al.* (1988) estimate the variations in the annual mean salinity above the halocline in the Gulf of Finland to contribute a ±2 cm change to annual mean sea levels. The local thermal expansion caused by the seasonal temperature variations of the sea surface layer amounts to a few centimetres.

In the small Baltic Sea, the differential gravitational force of the Sun and Moon is not in itself enough to generate strong tidal motions. On the other hand, the Danish Straits restrict the penetration of the tides from the North Sea into the Baltic Sea (Defant, 1961b; Lisitzin, 1974; Leppäranta and Myrberg, 2009). Local tidal amplitudes are only a few centimetres, the highest amplitudes of nearly 10 cm being observed near the Danish Straits and in the eastern Gulf of Finland (Witting, 1911; Defant, 1961b). Tides in the Baltic Sea are of diurnal or mixed type.

The Fennoscandian area around the Baltic Sea is characterized by postglacial land uplift – the recovery of the Earth’s crust from the deformation caused by the last ice age. This contributes to the apparent sea level changes seen from a coastal viewpoint. The absolute land uplift rates – given in relation to a fixed reference point, not the mean sea level – on the Finnish coast vary from 3–4 mm/yr in the eastern part of the Gulf of Finland up to 9–10 mm/yr around the Quark area between the Bothnian Sea and the Bothnian Bay (Lisitzin, 1964; Ekman, 1996; Lidberg *et al.*, 2007; Papers III and IV).

# 3 OBSERVED SEA LEVELS ON THE FINNISH COAST

## 3.1 DATA

Regular sea level measurements on the Finnish coast commenced in the mid-19th century (Renqvist, 1931), sea levels being then recorded manually a few times a day. Continuous measurements started in late 1887, when the first Finnish mareograph, an automatic tide gauge consisting of a float in a well and a recording apparatus, was established at Hanko. Today, there are 13 such tide gauges operating on the Finnish coast (Table 3.1, Fig 3.1). The most recent of these tide gauges is located at Rauma, in operation since 1933.

The sea level data were generally digitized and quality checked at a 4-hour resolution up to 1970 and hourly since then, first by the Finnish Institute of Marine Research, and recently by the Finnish Meteorological Institute. To obtain a homogeneous time series, this study is based on 4-hourly sea level values, along with monthly and annual means calculated from the data. The 79–124-year long data series have been extensively quality-controlled and checked. Details regarding the data quality and some of the problems encountered are presented in Paper I.

The sea level time series are interrupted by gaps ranging from some hours up to more than two years due to various reasons. These gaps were patched by interpolating the sea level data from adjacent stations, where- and whenever possible. Interpolation is considered a reliable method for estimating sea levels on the Finnish coast, as the sea level variations at adjacent tide gauges are highly correlated. For detrended 4-hourly sea level observations the correlation coefficients between any adjacent tide gauges on the Finnish coast are $r > 0.97$. The effect of interpolation on the annual mean sea levels was analyzed in Paper IV. After interpolation, generally less than 0.4% of the values are missing from the time series. (The only exception is Hanko, where more values are missing during the early decades prior to 1920.)

When presenting sea level data, it is in many cases necessary to define the reference or “zero” level. In this study, the main consideration is given to sea level changes, anomalies, or differences. This makes the actual choice of the reference level irrelevant, and excludes the possibility that this (arbitrary) choice might affect the results. However, occasionally two alternative reference levels are used, mainly for purposes of illustrating the data.

The Finnish height system N2000 (Saaranen *et al.*, 2009) is based on the third precise levelling of Finland, carried out in 1978–2006. The datum of this system is the Normaal Amsterdams Peil (NAP), the same as for the European Vertical Reference Frame 2000 (EVRF2000). Finnish tide gauges are annually levelled to this height system. Essentially, from a sea level viewpoint, the height reference N2000 is fixed in relation to the bedrock. Another option is to have a height reference that follows the mean sea level. One height reference of the latter type, the theoretical mean sea level (abbreviated MW), is commonly used in Finland as a practical reference level for sea level observations. The theoretical mean sea level is a time-dependent expectation value for the long-term mean sea level, based on a piecewise-linear estimate of the sea level trend. The definition of the theoretical mean sea level, based on the works of Hela (1953), Lisitzin (1964) and Vermeer *et al.* (1988), was summarised in Paper II.

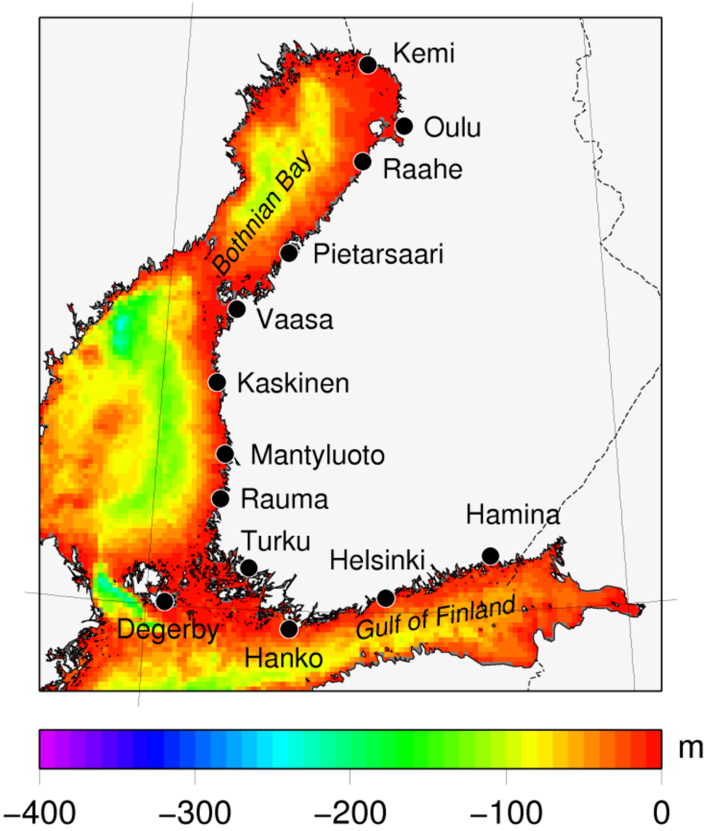



FIGURE 3.1. Locations of tide gauges on the Finnish coast (bottom topography from Seifert *et al.*, 2001).

TABLE 3.1. The Finnish tide gauge data used in this study, number of missing monthly mean sea levels (after patching by interpolation), as well as percentages of missing, interpolated or corrected 4-hourly sea level values.

| Tide gauge | Location | Years of data used | Missing monthly means | Missing 4-hourly values (%) | Interpolated or corrected 4-hourly values (%) |
|---|---|---|---|---|---|
| Kemi | 65°40'N, 24°31'E | 1923–2011 | | 0.13 | 4.6 |
| Oulu | 65°02'N, 25°25'E | 1923–2011 | 1 | 0.22 | 6.9 |
| Raahe | 64°40'N, 24°24'E | 1923–2011 | | 0.13 | 9.1 |
| Pietarsaari | 63°43'N, 22°41'E | 1922–2011 | | 0.08 | 2.0 |
| Vaasa | 63°05'N, 21°34'E | 1922–2011 | | 0.03 | 8.4 |
| Kaskinen | 62°21'N, 21°13'E | 1927–2011 | 2 | 0.34 | 4.6 |
| Mäntyluoto | 61°36'N, 21°28'E | 1925–2011 | 2 | 0.26 | 1.8 |
| Rauma | 61°08'N, 21°26'E | 1933–2011 | | 0.12 | 0.8 |
| Turku | 60°26'N, 22°06'E | 1922–2011 | | 0.06 | 3.9 |
| Degerby | 60°02'N, 20°23'E | 1924–2011 | | 0.01 | 6.3 |
| Hanko | 59°49'N, 22°59'E | 1888–2011 | 5 | 1.61 | 15 |
| Helsinki | 60°09'N, 24°58'E | 1904–2011 | | 0.00 | 1.1 |
| Hamina | 60°34'N, 27°11'E | 1929–2011 | | 0.01 | 2.5 |

## 3.2 VARIABILITY

In the past the mean sea level on the Finnish coast has declined (Fig. 3.2; e.g. Lisitzin, 1964; Vermeer *et al.*, 1988; Paper II). On top of the long-term trend, the decadal variations amount to a few centimetres and annual means vary up to 20 cm from year to year. The short-term variations depend on location, and range from about 1.7 metres at Degerby in the Archipelago Sea up to more than three metres at Hamina, Kemi and Oulu near the closed ends of the Gulf of Finland and the Bothnian Bay (Fig. 3.3a). Outside the limits of the Finnish coast, the variations at the innermost end of the Gulf of Finland are even larger. At St. Petersburg, the highest sea level observed is 421 cm above an approximate mean sea level (Averkiev and Klevannyy, 2010), indicating a total sea level variability exceeding five metres.

The sea level variations have a distinct seasonal cycle (Fig. 3.3b). The variations are largest in wintertime, resulting in the extreme sea level values usually occurring then. At every Finnish tide gauge except Kemi, the highest sea levels have been measured during storm events in January. At Kemi, a storm raised the sea level there to a record height in September 1982 (Table 3.2). The sea level minima have been measured between October and April, many of them also occurring in January. The seasonal sea level behaviour on the other coasts of the Baltic Sea is similar: the maximum variability occurs in late autumn and early winter (e.g. Samuelsson and Stigebrandt, 1996; Suursaar and Sooäär, 2007; Richter *et al.*, 2011).

It is apparent from Table 3.2 that the absolute values of the sea level maxima are 1.2–1.8 times larger than the absolute values of the minima. This is due to the asymmetric frequency distribution of sea level values on the Finnish coast (Fig. 3.4).

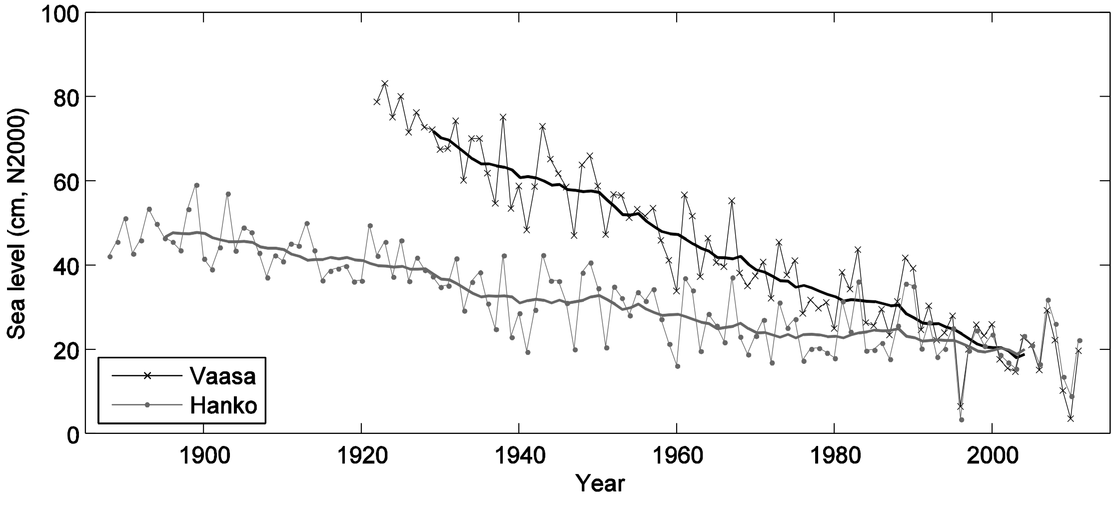



FIGURE 3.2. Annual mean sea levels measured at Vaasa (1922–2011) and Hanko (1888–2011). The 15-year running averages are also shown (thick lines).

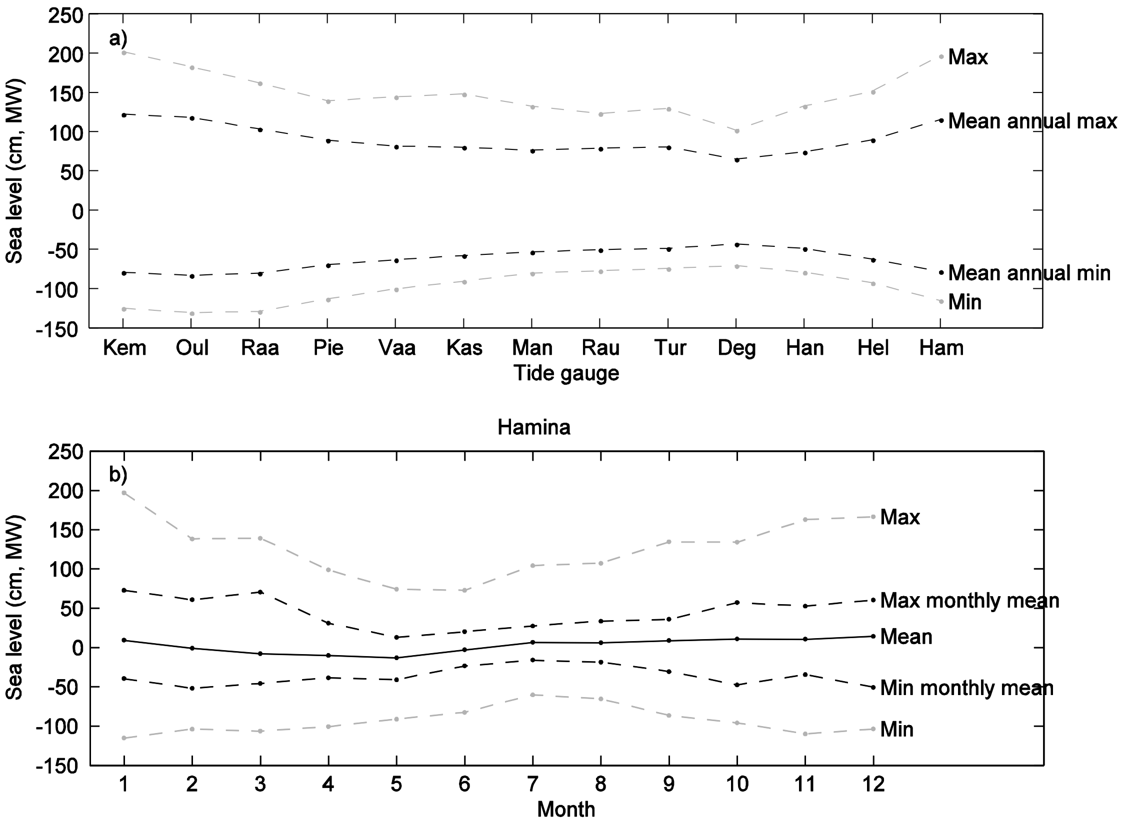



FIGURE 3.3. Short-term sea level variations on the Finnish coast, in relation to the theoretical mean sea level: a) extreme values and average annual maxima/minima observed along the coast; b) monthly extremes and the average and extreme monthly means at Hamina in 1929–2011.

TABLE 3.2. The extreme sea levels measured at the Finnish tide gauges in relation to the "theoretical mean sea level" (an estimate corresponding to the changing long-term mean sea level, see Paper II for details).

| Tide gauge | Maximum (cm, date) | | Minimum (cm, date) | |
|---|---|---|---|---|
| Kemi | +201 | 22.9.1982 | –125 | 21.11.1923 |
| Oulu | +183 | 14.1.1984 | –131 | 14.1.1929 |
| Raahe | +162 | 14.1.1984 | –129 | 4.10.1936 |
| Pietarsaari | +139 | 14.1.1984 | –113 | 4.10.1936 |
| Vaasa | +144 | 14.1.1984 | –100 | 14.1.1929 |
| Kaskinen | +148 | 14.1.1984 | –91 | 31.1.1998 |
| Mäntyluoto | +132 | 14.1.1984 | –80 | 10.4.1934 |
| Rauma | +123 | 16.1.2007 | –77 | 10.4.1934 |
| Turku | +130 | 9.1.2005 | –74 | 10.4.1934 |
| Degerby | +102 | 14.1.2007 | –71 | 10.4.1934 |
| Hanko | +132 | 9.1.2005 | –79 | 28.1.2010 |
| Helsinki | +151 | 9.1.2005 | –93 | 28.1.2010 |
| Hamina | +197 | 9.1.2005 | –115 | 28.1.2010 |

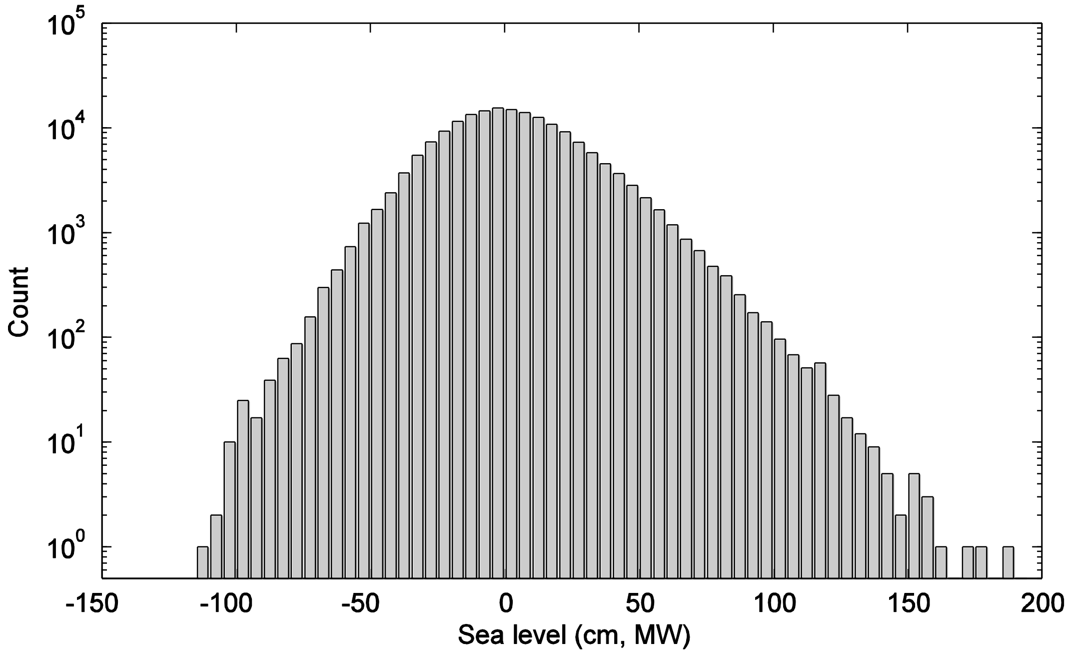



FIGURE 3.4. Frequency distribution of 4-hourly sea level values measured at Hamina in 1929–2011, in relation to the theoretical mean sea level. The observed all-time maximum at Hamina (+197 cm, Table 3.2) occurred in between the 4-hourly sampling instants.

# 4 METHODS

## 4.1 REASONING FOR THE STATISTICAL METHOD

The most important factors affecting sea level variations on the Finnish coast are wind, air pressure, land uplift, and large-scale sea level rise (see Section 2). To meet the objectives of this study, a method was applied to separate the effects of these on the observed sea levels.

The principles of the physical mechanisms by which air pressure and wind stress affect sea levels have been known for a long time (e.g. Witting, 1918; Hela, 1944). However, in practice, the relationship is complicated because of the different spatial and temporal scales involved for the various processes. Short-term variations in air pressure and wind affect the Baltic Sea as if it were a closed basin, but their effect on sea levels at different coastal sites is affected by the complicated topography of the Baltic Sea with its many sub-basins. In addition, seiches, which are a kind of secondary response to the atmospheric factors, complicate the situation. The long-term variations, on the other hand, are determined by the limited water transport in and out of the Baltic Sea. This transport is itself controlled by the wind and pressure conditions over the Baltic Sea as well as those over the North Sea.

To avoid the complications of the physical approach – which essentially would necessitate the use of a dynamical model – this study is based on statistical analyses. The objective is to find a simple statistical relationship between sea level and atmospheric factors that would describe the sea level variations to as great an extent as possible.

Such a method only describes the statistical connection between wind or pressure and sea levels. It cannot reveal the physical mechanism, especially as wind and pressure are mutually correlated. For instance, westerly winds and low air pressure separately lead to higher sea levels on the Finnish coast, but as westerly winds and low air pressure often occur together in connection with cyclonic activity, which of the two physical mechanisms is involved, and to what extent? Resolving this is therefore outside the scope of this study.

## 4.2 COMPONENT-WISE ANALYSIS OF SEA LEVEL VARIATIONS

Considering the abovementioned main factors, the observed sea level $h$ at the tide gauge $i$ at a 4-hourly time instant $t$:

$$h(t,i) = R_{N2000}(t_0,i) + h_L(t,t_0,i) - u(i)(t-t_0) + w(t,i) + s(t,i) \tag{4.1}$$

consists of

- the <u>levelling constant</u> $R_{N2000}$, which relates the sea level values to the height system N2000 and reference time $t_0$
- the <u>large-scale sea level change</u> $h_L$ since the reference time $t_0$, including the regional effects of ocean density and circulation changes, melting of ice sheets, glaciers and ice caps and other global-scale phenomena
- the <u>land uplift</u> $u(t–t_0)$ since the reference time, proceeding at the local rate $u$
- an estimate $w$ for the <u>atmosphere-related sea level variations</u> and
- <u>other sea level variations</u> $s$, containing variations due to density changes, freshwater input, tides and other factors, as well as the part of the atmosphere-related variations that the estimate $w$ cannot capture.

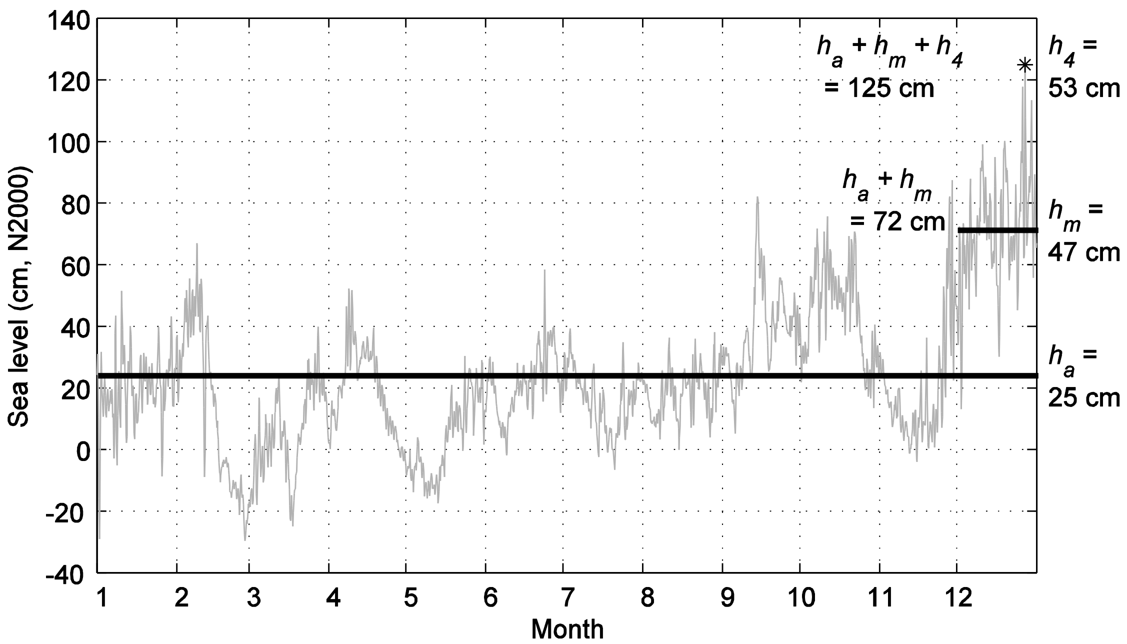



FIGURE 4.1. Dividing a sea level value $h$, given in the height system N2000, into annual mean ($h_a$), monthly mean anomaly ($h_m$) and 4-hourly anomaly ($h_4$).

These components can be further divided into different time scales (see Fig. 4.1):

$$\begin{aligned} h(t,i) &= h_a(y,i) + h_m(m,i) + h_4(t,i) \\ w(t,i) &= w_a(y,i) + w_m(m,i) + w_4(t,i) \\ s(t,i) &= s_a(y,i) + s_m(m,i) + s_4(t,i) \end{aligned} \tag{4.2}$$

where $h_a(y,i)$ is the annual mean sea level, $h_m(m,i)$ is the monthly mean anomaly or deviation from the annual mean, and $h_4(t,i)$ is the 4-hourly anomaly or deviation from the monthly mean at time instant $t$, in year $y$ and month $m$, and respectively for $w(t,i)$ and $s(t,i)$.

Separating the inter-annual variations and monthly mean anomalies in Eq. 4.1 leads to:

$$\begin{aligned} h_a(y,i) &= R_{N2000}(y_0,i) + h_L(y,y_0,i) - u(i)(y-y_0) + w_a(y,i) + s_a(y,i) \\ h_m(m,i) &= w_m(m,i) + s_m(m,i) \end{aligned} \tag{4.3}$$

where the large-scale sea level rise and the land uplift were considered to proceed so slowly that their intra-annual changes are negligible (the rates are less than 1 cm/yr, while the intra-annual variations are of the order of several tens of centimetres). Thus they were taken into account only in the inter-annual variations. To be precise, the term $s_m(m,i)$ actually contains a small contribution from these long-term effects.

Separation of the observed monthly mean sea levels into the components presented in Eq. 4.3 is started in Section 5 by constructing estimates for the atmosphere-related terms $w_a$ and $w_m$. Statistical methods are developed to construct these estimates using the observed atmospheric data as input. These estimates serve as tools for studying the role of the atmospheric factors on sea level variations in further analyses.

First, the estimate for $w_m$ allows the separation of the monthly sea level variations $h_m$ into atmosphere-related variations $w_m$ and the other variations $s_m$. The changes in the variability of these are studied in Section 6.1. The role of the atmospheric factors in these changes is examined as follows. Any observed change in behaviour that shows up in $w_m$ and not in $s_m$, is considered to be related to changes in the atmospheric conditions, as $w_m$ is based on atmospheric data. On the other hand, changes that show up in $s_m$ can be due to changes in other factors affecting sea levels, or due to atmosphere-related changes which the estimate $w_m$ can not capture.

In Sections 6.2 and 6.3, trends in the extremes and probability distributions of the 4-hourly sea level variations $h_m + h_4$ are studied. The contributions from different time scales and atmospheric factors on these trends are studied by separating the three components of which the intra-annual variations consist:

- atmosphere-related monthly mean variations $w_m$
- other monthly mean variations $s_m$
- intra-monthly variations $h_4$

and studying which of these components are involved in the observed changes.

The inter-annual variations are studied in Section 7. Subtracting the estimated atmosphere-related variations $w_a$ (obtained in Section 5) from the observed annual mean sea levels $h_a$ yields a reduced annual mean sea level $h_r$:

$$h_r(y,i) = R_{N2000}(y_0,i) + h_L(y,y_0,i) - u(i)(y-y_0) + s_a(y,i) \tag{4.4}$$

which allows studies of the long-term changes mainly consisting of the large-scale sea level rise and the land uplift. As will be shown, excluding the atmosphere-related variations substantially reduces the inter-annual variability of $h_a$ and allows a more precise determination of the long-term trends.

### 4.3 Some issues not considered in this analysis

The estimates $w_m$ and $w_a$ for the atmosphere-related sea level variations are based on a statistical relationship. This does not result in an accurate representation of the physical relationship, but rather gives an estimate that necessarily contains some uncertainty. This uncertainty – the inadequacy of the statistical relationship in capturing all the variations related to atmospheric factors – is included in the terms $s_m$ and $s_a$. This should be kept in mind when interpreting the results.

As mentioned in Section 2, the seasonal ice cover attenuates the effect of wind stress on redistributing water in the Baltic Sea. The physical, and thus also the statistical, relationship between atmospheric factors and sea levels differs during different ice conditions (Lisitzin, 1957). This could be studied by including ice cover information in the analyses – an issue not pursued here, but left for future studies.

Wind and air pressure also affect intra-monthly sea level variations (Table 2.1). In this study, no attempt is made to divide the intra-monthly variations into atmosphere-related and other components, as this study only focuses on the effect of atmospheric factors on monthly mean sea levels. Further analyses of the relationship between atmospheric factors and sea levels on shorter time scales are left for future studies. Such study might give further insight into the role of atmospheric influence on extreme sea level events, for instance.

# 5 ATMOSPHERE-RELATED SEA LEVEL VARIATIONS

## 5.1 NAO INDEX AND SEA LEVELS

Perhaps the most thoroughly-studied statistical correlation regarding the Baltic sea levels and atmospheric phenomena is that between the sea levels and the NAO index (e.g. Heyen *et al.*, 1996; Kahma, 1999; Andersson, 2002; Jevrejeva *et al.*, 2005; Dailidienė *et al.*, 2006; Hünicke and Zorita, 2006; Suursaar *et al.*, 2006; Suursaar and Sooäär, 2007; Papers I–III).

The NAO index describes the general air pressure conditions over the North Atlantic, being the leading pattern of weather and climate variability over the Northern Hemisphere. There are several ways to define the NAO index regarding the choice of pressure data and normalization, or the use of different linear or nonlinear analysis techniques on the air pressure field (e.g. Hurrell and Deser, 2009). In this study, the NAO index is defined as the wintertime (December–March) difference between normalized pressure anomalies at Gibraltar and a composite of sites in south-western Iceland (Jones *et al.*, 1997). This variant of the NAO index was used in Papers II and III. In Paper I, a slightly different version was used, but it was later discovered that the normalized Gibraltar–Iceland index better correlates with sea levels on the Finnish coast.

The different correlations when different versions of the NAO index are used can be explained as follows. The choice of pressure stations and normalization affects the way the index represents the pressure gradients, and also which variations are emphasized. For instance, normalization affects the relative importance of the Iceland area pressure variations in relation to the southern variations. This determines how well the index describes the specific physical conditions that affect the Baltic sea level.

In Paper II, the variations in the winter (December–March) mean NAO index were shown to explain 37–46% of the inter-annual sea level variability on the Finnish coast (Fig. 5.1), when the long-term trend was excluded. The southwestern Baltic Sea exhibited a weaker correlation than the Finnish coast, the NAO index explaining only about 20% of the sea level variability. This is in accordance with the results obtained by Suursaar *et al.* (2006), who found a strong correlation with sea levels on the Estonian coast, and with those of Hünicke and Zorita (2006) and Stramska and Chudziak (2013): the correlation is less evident in the southern Baltic Sea.

The correlation between the NAO index and sea levels is especially strong in wintertime. Andersson (2002) found a significant correlation during the winter months and a low correlation during spring and summer between the monthly mean Gibraltar–Iceland pressure difference and the monthly mean Baltic sea level. Hünicke and Zorita (2006) found the correlations between the Baltic sea levels and the NAO index to be predominately weaker in summer than in winter, and Suursaar and Sooäär (2007) found the highest correlations in winter for the sea levels on the Estonian coast. This is also connected to the fact that the annual mean sea levels on the Finnish coast correlate with the wintertime NAO index. The sea level varies from year to year more in winter than in summer (Fig. 3.3b). Thus, the relative importance of the winter months in determining the variability of the annual mean is greater than that of the summer months.

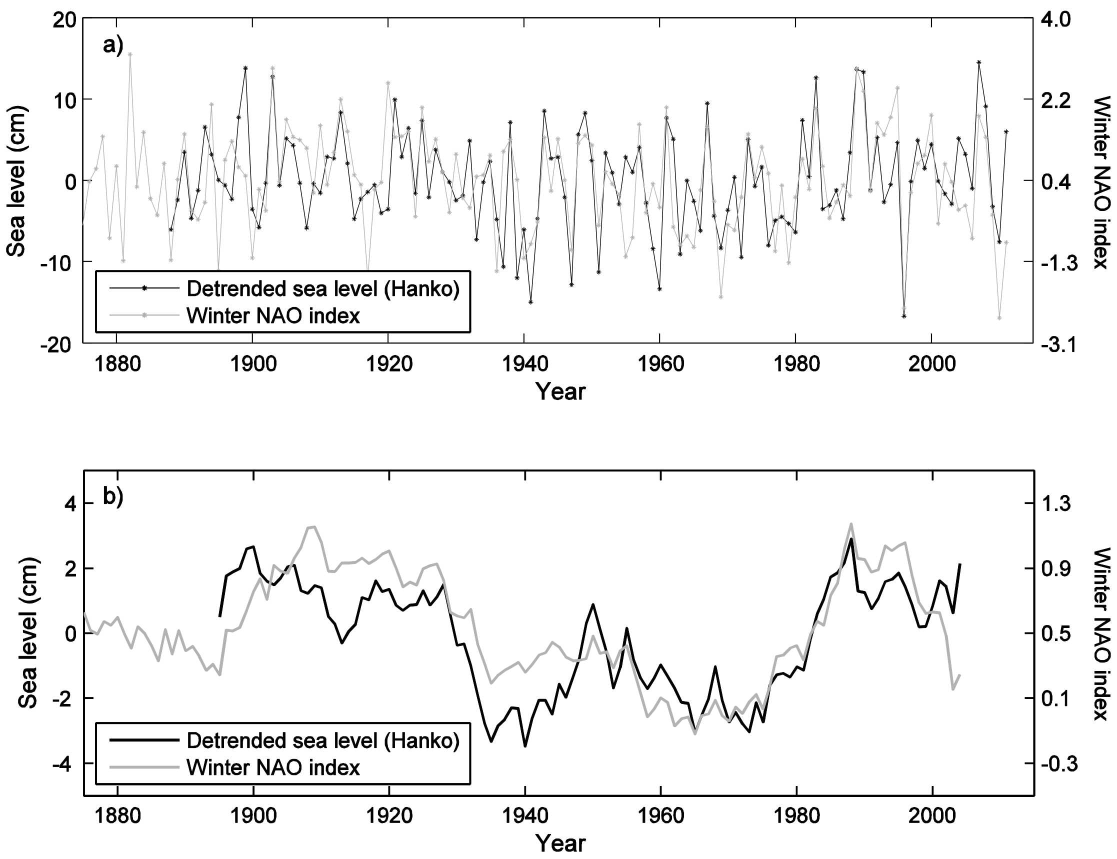



FIGURE 5.1. The winter (Dec–Mar) NAO index and annual mean sea levels at Hanko, detrended by removing the linear trend: a) annual values and b) 15-year running averages.

## 5.2 LOCAL AIR PRESSURE GRADIENTS AND GEOSTROPHIC WINDS

The NAO index represents the atmospheric conditions on the scale of the entire North Atlantic. It is worth considering whether more local factors might not better explain the local sea level variations.

Lisitzin (1962) studied the variation of the water volume of the Baltic Sea, as represented by the sea level measured at Degerby close to the centre of the Baltic Sea basin, as a function of the air pressure gradient between Malmö and Mariehamn, or Malmö and Gothenburg. The monthly means of these showed a correlation with $r = 0.5$–$0.6$, while a corresponding correlation was also found between the pressure gradient and the surface current in the Danish Straits.

Lehmann *et al.* (2002) defined a Baltic Sea Index (BSI) as the difference of normalized sea level pressure anomalies at Szczecin (Poland) and Oslo (Norway). Correlation with the BSI accounts for about 50% of the sea level variability at Landsort on the west coast of the Baltic Proper, which represents the volume change of the Baltic Sea. They concluded that the BSI, which represents the meridional pressure gradient over a distance of about 600 km, includes the variability of synoptic-scale pressure gradients that are not included in the NAO, which is based on a distance of about 3000 km.

Andersson (2002) studied the correlation between the Baltic sea level and the Baltic Atmospheric Circulation (BAC) index, which was defined as a combination of pressure differences closer to the Baltic Sea entrance, between de Bilt and Bergen and between Gibraltar and Helsinki. The BAC index explained more than 80% of the sea level winter variance ($r$ = 0.91), and also correlated well with the Baltic sea level during autumn ($r$ = 0.86) and summer ($r$ = 0.82). During spring the correlation with the BAC index was lower ($r$ = 0.64) but still significant. Both the correlation with the NAO index and the BAC index showed some temporal variation, but the correlation with the BAC index was always high compared to the correlation with the NAO index.

In Paper IV, the correlation of the annual mean geostrophic wind with the sea levels on the Finnish coast was studied. The geostrophic wind ($U_g$, $V_g$), calculated as:

$$U_g = -\frac{1}{f\rho}\frac{\partial p}{\partial y}, \quad V_g = \frac{1}{f\rho}\frac{\partial p}{\partial x} \tag{5.1}$$

where $f$ stands for the latitude-dependent Coriolis parameter, and $\rho$ for the air density, essentially represents a horizontal air pressure gradient, apart from the slight nonlinearity due to air density being pressure-dependent.

The geostrophic wind is defined as the air flow for which the Coriolis force exactly balances the horizontal pressure gradient, this resulting in a flow along the isobars. The surface wind speed, usually measured a few metres above the ground, is generally smaller than the geostrophic wind speed, due to the frictional force. It is also directed towards lower pressure, that is, towards the left of the geostrophic wind in the northern hemisphere (Holton, 1972).

The sea level is naturally affected by an interaction with the real surface wind. However, as the goal of this study is not in determining a quantitative physical relationship, but rather a statistical one, the use of the geostrophic wind is justified. The geostrophic wind can be seen as a kind of “atmospheric index” that represents both the wind field and the air pressure gradients.

The use of the geostrophic wind instead of the surface wind is further justified by the better availability of reliable and homogeneous long-term observation time series of pressure compared to wind. Relocations of stations as well as environmental changes have no significant effect on pressure records. In contrast, wind observations are very sensitive to local topography and obstacles. Relocation of observation sites or environmental changes in the vicinity of wind stations can easily result in inhomogeneities in the records (BACC author team, 2008).

The geostrophic winds for this study (Paper IV) were calculated from daily mean sea level pressure fields for the years 1899–2011 (Data Support Section/ Computational and Information Systems Laboratory/National Center for Atmospheric Research/University Corporation for Atmospheric Research *et al.*, 1979; Trenberth and Paolino, 1980). In the dataset, pressure was available on a 5° latitude/longitude grid over an area extending from 15°N to 85°N. The geostrophic winds were first calculated at the intermediate points of the grid and then interpolated on to the 5° latitude/longitude grid, which essentially results in each grid point value representing a gradient over a 10° spatial span. When calculating the air density, a constant temperature of 283K was assumed.

The correlation of sea levels on the Finnish coast with the geostrophic winds at each grid point over an area covering the Baltic Sea and surroundings (from 45°N to 75°N and 20°W to 40°E) was tested. The correlation was strongest for the zonal wind at a grid point over the southern Baltic Sea (55°N, 15°E), correlation coefficients ranging from 0.92 to 0.94. This zonal wind explains twice as large a percentage – 84–89% – of the inter-annual sea level variability on the Finnish coast as the NAO index. The meridional wind did not correlate with sea levels on the Finnish coast, correlation coefficients ranging from 0.21 to 0.41 (Table 2 of Paper IV).

### 5.3 Monthly mean geostrophic wind and air pressure

As the atmospheric factors act on sea levels on shorter time scales than a year (Table 2.1), and as both wind and air pressure exhibit a clear seasonality in their behaviour, it is reasonable to study their relationship with sea levels at a monthly resolution. Monthly mean air pressures and geostrophic winds were calculated from the daily mean sea level pressure fields on a 5° latitude/longitude grid, as explained above.

Correlations between the detrended monthly mean sea levels and the detrended geostrophic winds and air pressures were calculated. The detrending (removal of a linear trend) effectively removes most of the sea level variations caused by land uplift or large-scale sea level rise, which – as a first approximation – have proceeded linearly (Fig. 3.2). This linearity approximation is not exactly valid, as will be shown in Section 7.2. However, the variability of the monthly mean sea levels is of the order of several tens of centimetres (Fig. 3.3), while the deviations from linearity in the long-term trend are a few centimetres at most. In addition, assuming that there is a relationship between sea level and wind or pressure, detrending the sea level time series also eliminates a possible trend connected to a trend in the atmospheric factors. Thus, for the sake of conformity, the wind and pressure time series were also detrended to eliminate the corresponding trend. Physically, the relationship between them and sea level is then extracted from the correlation between the month-to-month anomalies, the variabilities of which are actually much larger than the linear trends.

Analogously with the annual means studied in Paper IV, when winds in an area extending over the entire Baltic Sea and surroundings (45–75°N, 20°W–40°E) were tested, the zonal winds at the point 55°N, 15°E showed the strongest correlation with Finnish sea levels. Correlations with different time lags – i.e., wind variations preceding the sea level variations, or vice versa – were calculated. This was motivated by the fact that the Danish Straits make the effect of wind partly cumulative, and introduce a delay into the response of the Baltic sea level (see Section 5.4 for further discussion). The monthly mean sea levels correlated with the monthly mean zonal geostrophic wind of the same month ($r$ = 0.80–0.84), and also with that of the previous month ($r$ = 0.52–0.56) (Table 5.1), but no other time lag showed any correlation. The meridional wind showed a much weaker correlation ($|r| < 0.28$) than the zonal wind.

For pressure, the grid point that showed the strongest correlation with sea levels on the Finnish coast varied, depending on the tide gauge location. It was always located further north than the tide gauge, however, being either (65°N, 25°E), (65°N, 20°E) or (70°N, 15°E). The monthly mean sea levels correlated with the air pressure of the same month ($r$ = –0.66 – –0.77) and the previous month ($r$ = –0.47 – –0.49), but again no other time lag showed any correlation.

The above-used monthly mean air pressure and zonal geostrophic wind are mutually strongly correlated, $r$ = –0.9. It appears that the atmospheric effect on sea levels is adequately described by choosing only one of them as a regressor. As the correlation coefficients were highest for the zonal geostrophic wind, it was chosen for further calculations. A two-variable linear regression was applied between the detrended monthly mean sea levels $h_d$ at tide gauge $i$ and the detrended zonal geostrophic wind $U_{g,d}$:

$$h_d(m,i) = p_{u0}(i)U_{g,d}(m) + p_{u1}(i)U_{g,d}(m-1) + \varepsilon(m,i) \tag{5.2}$$

to obtain regression coefficients $p_{u0}(i)$ and $p_{u1}(i)$ for the quantitative effects of the zonal geostrophic wind of the same month (*m*) and the previous month (*m*–1) on sea levels (Table 5.1), $\varepsilon(m,i)$ being the residual variations. An increase of 1 m/s in the mean zonal wind corresponds to 4 cm higher sea levels during the same month (coefficient $p_{u0}$), and 2 cm higher sea levels during the next month (coefficient $p_{u1}$). The regression coefficients are largest in the northern Bothnian Bay and eastern Gulf of Finland, and smallest in the Archipelago Sea.

The correlation coefficients between zonal winds and sea levels calculated for different calendar months at Hanko vary from 0.69 to 0.86 for month *m* and 0.29 to 0.70 for month *m*–1 (Fig. 5.2). The combination of these two explains 56–89% of the sea level variability the whole year round, the highest percentages being obtained in January–March and the lowest in May–July. The seasonal variations are in accordance with those found by Andersson (2002) when correlating the Baltic sea levels with the BAC index: the correlation is lowest in spring and highest in winter. The results are also in accordance with the findings that the correlation between the NAO index and sea levels is strongest in winter (Andersson, 2002; Hünicke and Zorita, 2006; Suursaar and Sooäär, 2007).

To study the decadal variations, the correlation was calculated for the sea levels at Hanko for overlapping 30-year periods during 110 years (Table 5.2). The correlation holds throughout the century ($R^2$ = 0.70–0.84), although there is a tendency towards a stronger correlation in the most recent decades. See discussion on this in Section 5.4.

TABLE 5.1. The correlation coefficients *r* and regression coefficients $p_{u0}$ and $p_{u1}$ for the relationship between the detrended monthly means of zonal geostrophic wind $U_g$ and sea levels at the Finnish tide gauges; $p_{u0}$ for the wind of the same month (*m*), and $p_{u1}$ for the wind of the previous month (*m*–1), see Eq. 5.2.

| Tide gauge | $r$, $U_g(m)$ | $r$, $U_g(m–1)$ | $p_{u0}$ (cm/ms$^{-1}$) | $p_{u1}$ (cm/ms$^{-1}$) |
|---|---|---|---|---|
| Kemi | 0.80 | 0.55 | 4.34 | 2.26 |
| Oulu | 0.81 | 0.56 | 4.26 | 2.25 |
| Raahe | 0.82 | 0.56 | 4.29 | 2.22 |
| Pietarsaari | 0.82 | 0.56 | 4.19 | 2.17 |
| Vaasa | 0.83 | 0.56 | 4.13 | 2.06 |
| Kaskinen | 0.83 | 0.55 | 4.09 | 2.05 |
| Mäntyluoto | 0.83 | 0.55 | 4.05 | 2.00 |
| Rauma | 0.83 | 0.56 | 3.99 | 1.96 |
| Turku | 0.82 | 0.54 | 4.05 | 1.95 |
| Degerby | 0.81 | 0.55 | 3.80 | 1.91 |
| Hanko | 0.81 | 0.53 | 3.92 | 1.91 |
| Helsinki | 0.82 | 0.52 | 4.17 | 1.93 |
| Hamina | 0.84 | 0.53 | 4.59 | 2.02 |

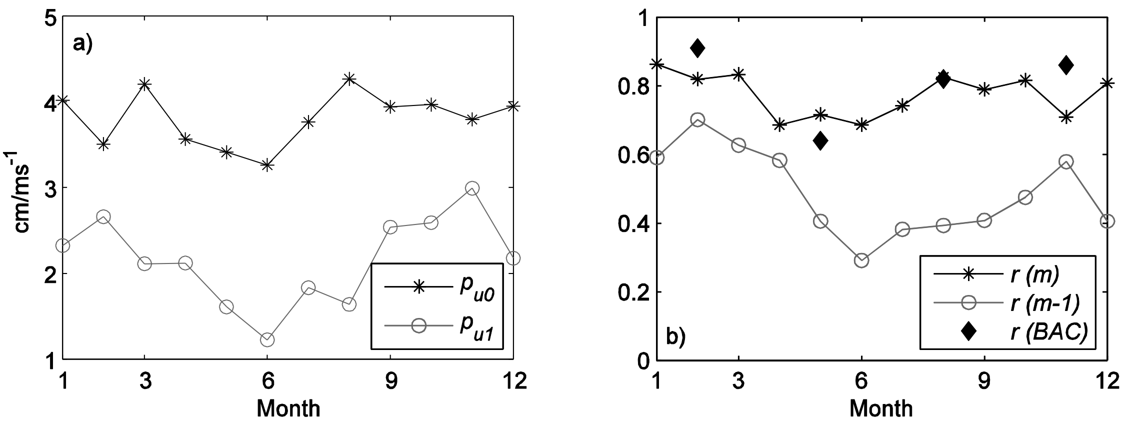



FIGURE 5.2. a) Regression coefficients $p_{u0}$ and $p_{u1}$ and b) correlation coefficients *r* between the monthly mean zonal geostrophic wind of the same (*m*) and previous (*m*–1) month and the sea levels at Hanko for different calendar months. The correlation coefficients from Andersson (2002) between the BAC index and the Baltic sea level are also shown.

TABLE 5.2. The correlation coefficients *r* and regression coefficients $p_{u0}$ and $p_{u1}$ for the relationship between the detrended monthly means of zonal geostrophic wind $U_g$ and sea levels at Hanko for different overlapping 30-year periods; $p_{u0}$ for the wind of the same month (*m*), and $p_{u1}$ for the wind of the previous month (*m*–1), see Eq. 5.2.

| Years | *r* $U_g(m)$ | *r* $U_g(m–1)$ | $p_{u0}$ (cm/ms$^{-1}$) | $p_{u1}$ (cm/ms$^{-1}$) |
|---|---|---|---|---|
| 1902–1931 | 0.77 | 0.47 | 3.74 | 1.78 |
| 1912–1941 | 0.76 | 0.48 | 3.68 | 1.93 |
| 1922–1951 | 0.77 | 0.46 | 3.81 | 1.96 |
| 1932–1961 | 0.77 | 0.49 | 3.80 | 2.01 |
| 1942–1971 | 0.80 | 0.50 | 4.03 | 2.02 |
| 1952–1981 | 0.83 | 0.56 | 4.22 | 1.95 |
| 1962–1991 | 0.86 | 0.57 | 4.22 | 1.92 |
| 1972–2001 | 0.86 | 0.59 | 4.09 | 1.85 |
| 1982–2011 | 0.85 | 0.60 | 3.97 | 1.91 |

## 5.4 MECHANISMS BEHIND THE CORRELATION

The effect of wind and air pressure on sea levels is a combination of several processes (Section 2), which together result in the correlation. As monthly means were studied, short-term effects such as seiche and local storm surges can be ignored, leaving water transport through the Danish Straits and redistribution of the Baltic Sea water between sub-basins.

It is apparent why the correlation between monthly mean zonal wind and sea levels on the Finnish coast shows up both instantly and with a time lag of up to one month. The redistribution of water due to wind stress or air pressure gradients takes very little time compared to a month. This is clear when recalling that the periods of the seiche oscillations are less than two days. Considering the water transport through the

Danish Straits, the effects of wind and pressure are cumulative: it is the *change* in the Baltic sea level, not the sea level value in itself, that depends on the zonal wind or the air pressure field. The transport, being primarily driven by the sea level difference over the straits, also depends on the amount of water previously accumulated in the Baltic Sea.

The strongest correlation with the monthly mean sea levels on the Finnish coast is exhibited by the geostrophic wind at a grid point located over the southern Baltic Sea (55°N, 15°E). This is in accordance with the mechanism being not a local one, but a phenomenon that operates over the entire Baltic Sea. The point 55°N, 15°E seems to be located promisingly close to the Danish Straits. However, the 5° pressure grid is too coarse for drawing conclusions; the zonal wind as defined actually represents a pressure gradient from 50°N to 60°N.

It is difficult to separate the two effects of internal water redistribution and water transport in the straits by using only sea level data from the Finnish coast, as there both mechanisms act on the same direction – a westerly wind raises the sea level. This should not be the case in the southwestern Baltic Sea, where water transport raises, but the internal redistribution lowers the sea level in westerly wind conditions – such as the sea level $h_2$ in Fig. 2.4a. This might explain why the correlation between sea levels and atmospheric factors is weaker in the southwestern part of the Baltic Sea than on the Finnish coast, as was shown for the NAO index by Hünicke and Zorita (2006) and Paper II. An analysis of the relationship between monthly mean geostrophic winds and sea levels over the entire Baltic Sea might thus give further insight into the separate roles of water transport and internal redistribution. This issue is left for future studies.

The relationship between zonal geostrophic wind and sea levels shows some decadal variation (Table 5.2): the correlation coefficients have positive trends. The reason for this is still unknown. Potential explanations include issues related to data quality during the earlier decades, or to an effect of changing ice conditions.

The correlation between Baltic sea levels and the NAO index is related to the same physical mechanisms as the effect of wind and local air pressure. A higher-than-average NAO index means a stronger-than-average north-south pressure gradient, corresponding to a stronger-than-average westerly geostrophic flow over northern Europe. There are also other mechanisms than those directly related to air pressure and winds that might contribute to the correlation between the NAO index and sea levels. A high NAO index also correlates with high precipitation and air temperature (Hurrell, 1995), which may have small effects on sea level. A statistical method alone does not distinguish between the different physical mechanisms.

### 5.5 Estimate for the atmosphere-related sea level variations

Using the regression coefficients obtained, estimates $w$ for the monthly atmosphere-related sea level variations at tide gauges $i$ were calculated as a function of the zonal geostrophic wind $U_g$:

$$w(m,i) = p_{u0}(i)U_g(m) + p_{u1}(i)U_g(m-1) \tag{5.3}$$

The annual means $w_a$ were obtained by averaging $w$ for each year; subtracting these from the monthly values $w$ yielded the monthly anomalies $w_m$, according to Eq. 4.2. As this study is limited to considering the monthly mean effect of wind, the 4-hourly anomalies of this estimate are $w_4 = 0$. The co-variation of the estimate $w_a$ with the observed annual mean sea levels $h_a$ is apparent, the estimate $w_a$ capturing 82–88% of the inter-annual variability of sea levels at different Finnish tide gauges, the coefficients of determination ($R^2$) ranging from 0.82 to 0.88 (Fig. 5.3a). The estimate also shows decadal variations that correspond to the observed sea level variations (Fig. 5.3b).

The co-variation of the monthly mean anomalies $w_m$ and $h_m$ is also apparent (Fig. 5.4a). The atmosphere-related estimate captures 76–81% of the variability of the observed monthly anomalies ($R^2$ = 0.76–0.81), the root-mean-square (rms) difference being 7–9 cm.

The monthly anomaly $w_m$ exhibits an average seasonal cycle similar to that of the observed sea levels $h_m$, the minimum occurring in May, and the maximum in winter (Fig. 5.4b). The difference between the average seasonal cycles of $h_m$ and $w_m$ ranges from –9 cm to +6 cm and is negative in Jan–Apr and positive in Jun–Nov at all the Finnish tide gauges.

In Paper IV, the corresponding estimate for the atmosphere-related variations was calculated based on a linear relationship between the annual mean zonal geostrophic wind and sea levels. The estimate explained 84–89% of the year-to-year variability of sea levels up to the year 2000. If calculated only up to year 2000, the atmosphere-related estimate $w_a$ calculated here explains 86–93% of the year-to-year variability. The lower correlation when the latest decade is included in the time series might result from the nonlinear acceleration of the previously linear background trend, which is further discussed in Section 7.2.

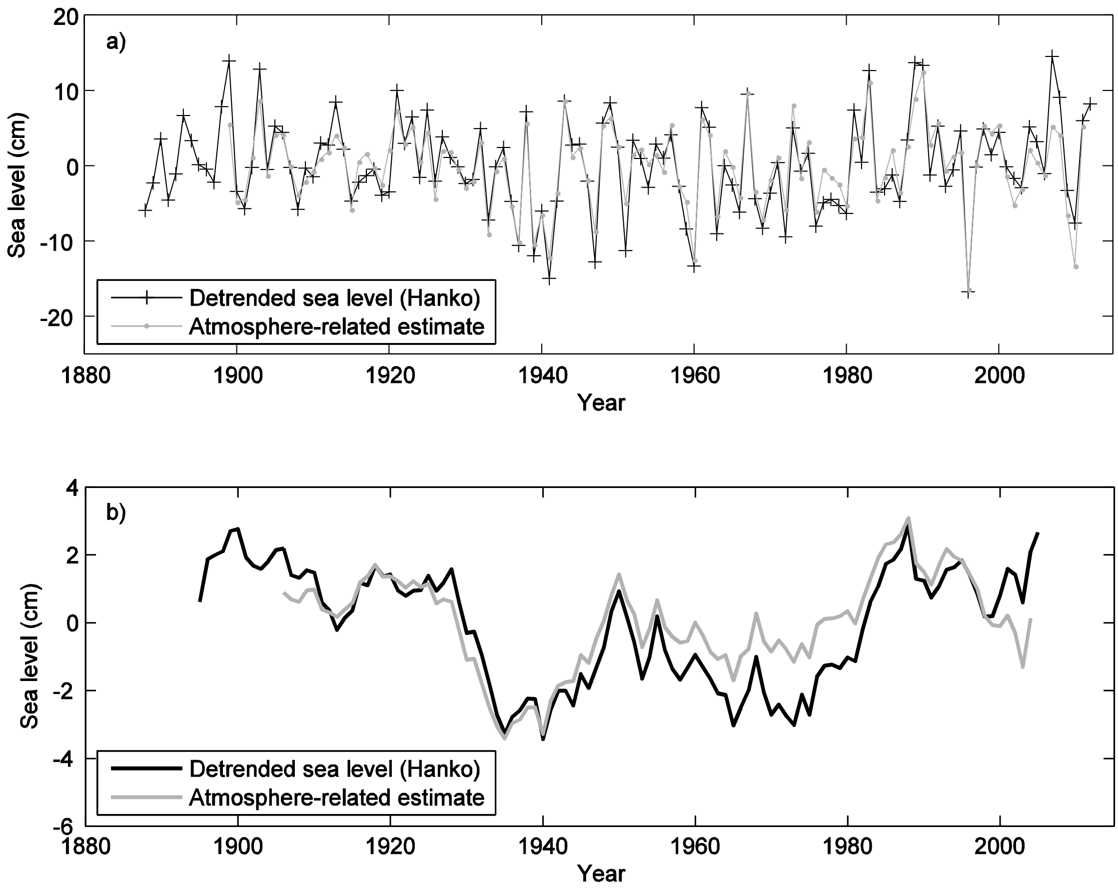



FIGURE 5.3. Sea levels at Hanko and the atmosphere-related sea level estimate, detrended by removing the linear trend: a) annual mean values and b) 15-year running averages.

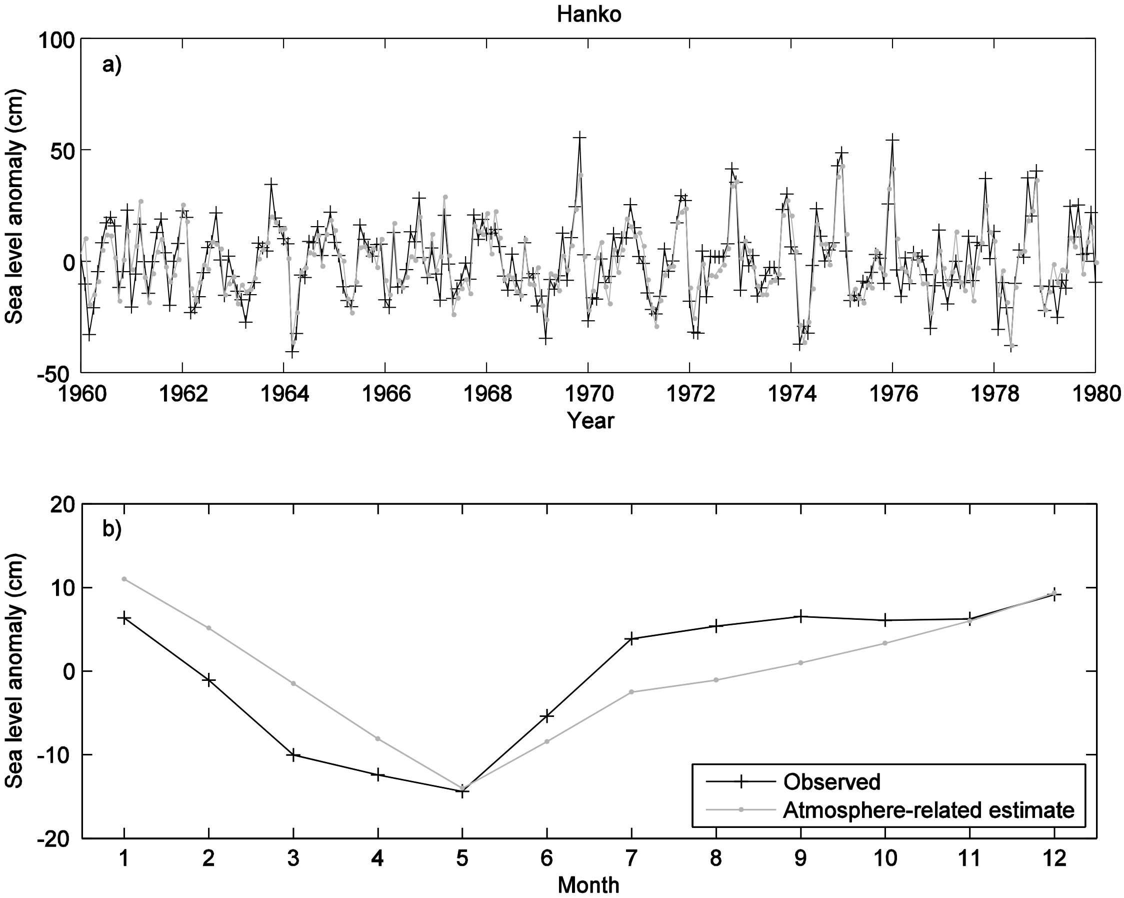



FIGURE 5.4. Monthly mean anomalies (deviations from the annual mean) of observed sea level and the atmosphere-related estimate at Hanko: a) an example of monthly mean time series (the year labels correspond to January), and b) the average seasonal cycle.

# 6 CHANGES IN SHORT-TERM VARIABILITY

## 6.1 SEASONAL VARIATIONS

Changes in the intra-annual sea level variability on the Finnish coast were thoroughly studied in Paper I. An increase in the amplitude of the 12-month spectral peak of monthly mean sea levels was found, indicating that the seasonal sea level variations have changed. Changes have also been reported in other parts of the Baltic Sea. The seasonal sea level behaviour at Stockholm on the Swedish coast has changed during the last two centuries (Ekman and Stigebrandt, 1990; Ekman, 1998): an increase in the sea levels in December–January and a decrease in February–March were found by Ekman (1998). These changes corresponded to changes in wind conditions with a phase lag of one month. Hünicke and Zorita (2008) reported an increasing trend in the mean sea level difference between winter and spring, this trend being almost uniform in different parts of the Baltic Sea. Suursaar *et al.* (2006) found an increase in the course of the 20$^{th}$ century, of 5 cm in the amplitude of the seasonal signal at Pärnu, on the Estonian coast. They concluded that the sea level rise, which was concentrated in November–March, correlated with increased local storminess and with a higher intensity of westerlies, as described by the AO and NAO indices. According to Dailidienė *et al.* (2006), the sea levels at Klaipeda on the Lithuanian coast have been rising more during the cold half-year (October–March) than in the warm half-year (April–September).

To study the changes in the seasonal cycle, and the role of the atmospheric factors in them, the averages of the monthly anomalies $h_m$, $w_m$ and $s_m$ were calculated for each calendar month in consecutive 20-year periods. The results for Helsinki are shown in Fig. 6.1. It appears that in 1970–1989, sea levels were higher than previously in November–December, while in 1990–2009, increased sea levels were observed in January–March. The maximum monthly mean shifted from September–October in early 20$^{th}$ century to December in 1970–1989 and further to January in 1990–2009. The changes in the atmosphere-related variations $w_m$ follow these changes, while the other variations $s_m$ have not changed.

The average linear trends in the monthly mean sea level anomalies from 1933 to 2011, the period during which all the Finnish tide gauges have been operating, are given in Table 6.1. Increasing trends in November–March and decreasing trends in April–October are generally seen both in the observations and in the atmosphere-related variations. The results of Hünicke and Zorita (2008) – an increase in the difference between winter (Nov–Jan) and spring (Mar–May) sea levels – are in accordance with the results obtained here. The results are also in line with the changes found by Suursaar *et al.* (2006) and Dailidienė *et al.* (2006).

The similarity of the changes of the seasonal cycle of $h_m$ and $w_m$ is to be expected, as the atmosphere-related variations contain about 80% of the variability of the monthly anomalies. As the other variations do not show any changes from decade to decade, this suggests that the changes seen in the seasonal cycle are related to changes in the monthly mean wind conditions. The changes in wind conditions are further discussed in Section 6.4.

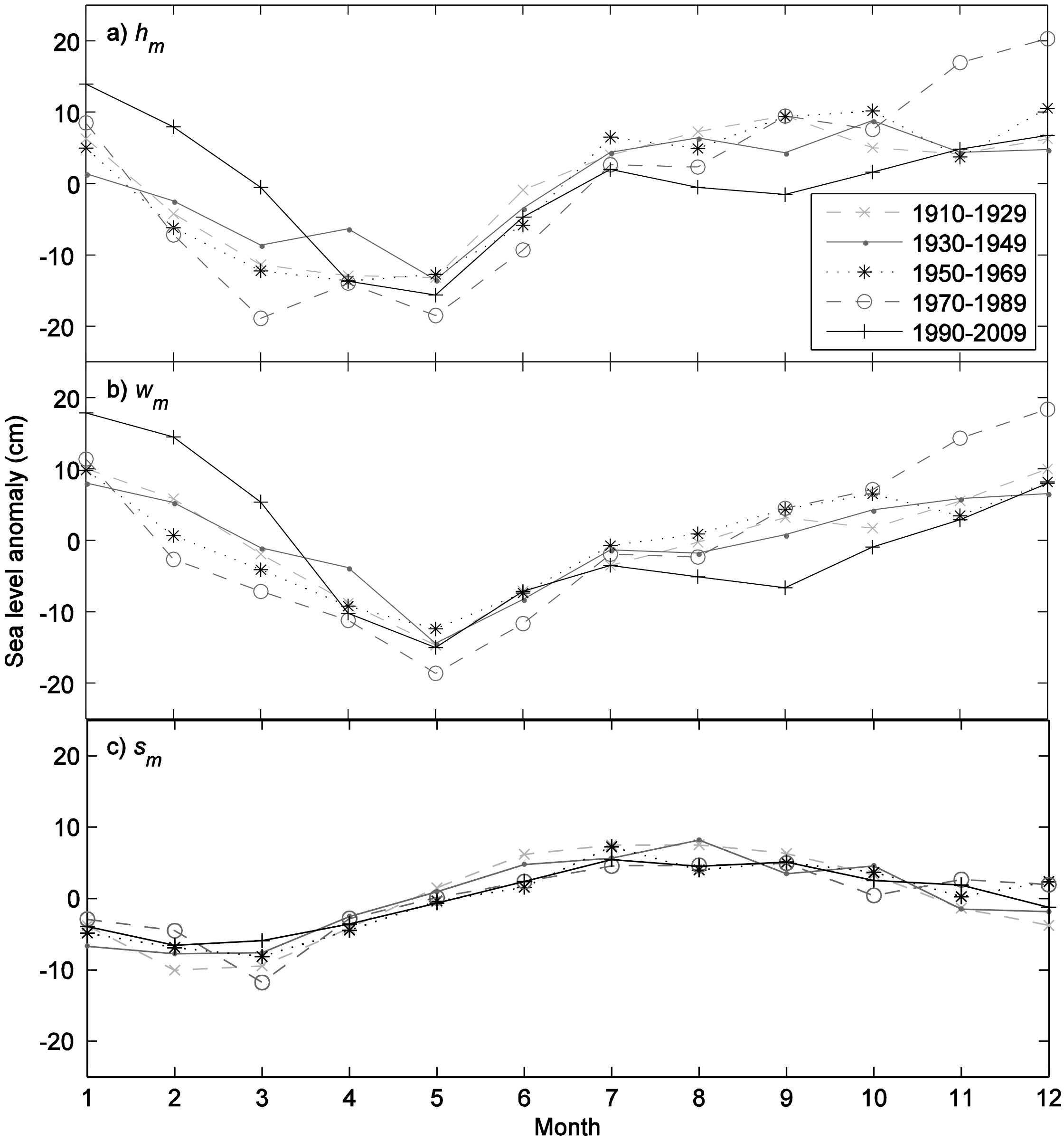



FIGURE 6.1. Average monthly anomalies (deviations from the annual mean) of a) observed sea level $h_m$, b) atmosphere-related sea level variations $w_m$ and c) other variations $s_m$ at Helsinki in successive 20-year periods.

TABLE 6.1. Linear trends in the monthly mean anomalies of the observed sea level $h_m$, atmosphere-related variations $w_m$ and other variations $s_m$ in 1933–2011. The values shown are averages over all the Finnish tide gauges.

| | Trend (mm/yr) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| $h_m$ | 1.6 | 1.1 | 0.9 | –1.2 | –0.3 | –0.3 | –0.6 | –1.1 | –0.5 | –0.7 | 0.7 | 0.4 |
| $w_m$ | 1.4 | 0.6 | 0.7 | –1.0 | –0.3 | 0.1 | –0.5 | –0.6 | –0.9 | –0.3 | 0.1 | 0.7 |
| $s_m$ | 0.2 | 0.5 | 0.2 | –0.2 | –0.0 | –0.4 | –0.1 | –0.5 | 0.4 | –0.4 | 0.6 | –0.3 |

### 6.2 Extremes

The annual maxima and minima of sea level were calculated from the intra-annual anomalies, or deviations from the annual mean ($h_m$ + $h_4$ in Eq. 4.2 and Fig. 4.1). Using such anomalies eliminates the effect of any long-term mean sea level changes, and allows analyses of the intra-annual variability, analogously to the use of monthly anomalies above. The linear trends in these annual extremes from 1933 to 2011 at the Finnish tide gauges are presented in Table 6.2. Apart from Kemi, the trends at the other tide gauges are statistically significant at the 99% level, according to Student's *t*-test. The trends in the minima are around zero and are not statistically significant.

The spatial distribution of the magnitudes of the trends is roughly in accordance with the spatial distribution of the extent of the intra-annual sea level variability: stations with larger variability show larger trends, excluding Kemi, which behaves anomalously. The tide gauge at Kemi was moved about 7 km in the 1970s, and is known to have had some practical problems, for which reasons the results for Kemi were considered less reliable than those of the other tide gauges in Paper I.

The magnitudes of the trends are generally larger than those presented in Paper I, where a similar analysis was conducted for sea level maxima from the establishment year of each tide gauge up to 1999. The addition of the twelve years of more recent data, and the exclusion of the earliest decades, reinforced the statistical significance of the trends, as only six tide gauges showed significant trends in Paper I.

Increasing trends in sea level maxima were also reported by Suursaar and Sooäär (2007) for the Estonian coast: an increase of 3.5–11.2 mm/yr, while the mean sea levels only showed an increase of 1.0–2.6 mm/yr. The trends are of similar magnitude or larger than those on the Finnish coast.

As presented in Section 4.3, the intra-annual anomalies studied above consist of the three components: $w_m$, $s_m$ and $h_4$. To study their individual roles in the observed trends, the trends in different combinations of these components were calculated for the years 1933–2011 and compared with the observed overall trends (Fig. 6.2). The trends in the maximum 4-hourly anomalies $h_4$ are –0.4 to +1.6 mm/yr, considerably smaller than the overall trends in the intra-annual maxima. Adding the atmosphere-related monthly anomalies to this increases the trends by 1.4–2.8 mm/yr, giving trends almost as high as those observed. Excluding the atmosphere-related anomalies and only including the other monthly anomalies $s_m$ does not increase the trends by more than about 0.6 mm/yr. As a conclusion, 1.4–2.8 mm/yr of the trends in the maxima are related to the effect of atmospheric factors on monthly mean sea levels.

The trends in the intra-monthly variations $h_4$ are largest in the inner parts of the Bothnian Bay and the Gulf of Finland (again excluding Kemi), which suggests that this trend is related to factors which have their largest effects at the closed ends of the bays. On the other hand, the part of the trend which is implicitly related to the atmospheric conditions – 1.4–2.8 mm/yr – shows a different spatial distribution, with largest values in the northern Bothnian Sea and smallest values in the Gulf of Finland.

TABLE 6.2. Trends in the annual extreme sea level anomalies (4-hourly deviations from the annual means) in 1933–2011. Statistical significances are based on Student's *t*-test.

| | Annual maxima | | Annual minima | |
|---|---|---|---|---|
| Tide gauge | Trend (mm/yr) | Sign. (%) | Trend (mm/yr) | Sign. (%) |
| Kemi | 1.9 | 89 | –0.5 | 44 |
| Oulu | 3.5 | 99 | –0.4 | 37 |
| Raahe | 3.1 | 99 | 0.2 | 24 |
| Pietarsaari | 3.2 | 99 | –0.1 | 17 |
| Vaasa | 2.8 | 99 | –0.3 | 43 |
| Kaskinen | 2.6 | 99 | –0.5 | 65 |
| Mäntyluoto | 2.5 | 99 | –0.2 | 33 |
| Rauma | 2.8 | 99 | –0.2 | 33 |
| Turku | 2.8 | 99 | 0.2 | 27 |
| Degerby | 2.1 | 99 | 0.1 | 26 |
| Hanko | 2.5 | 99 | 0.4 | 55 |
| Helsinki | 3.2 | 99 | 1.0 | 93 |
| Hamina | 3.9 | 99 | 0.2 | 21 |

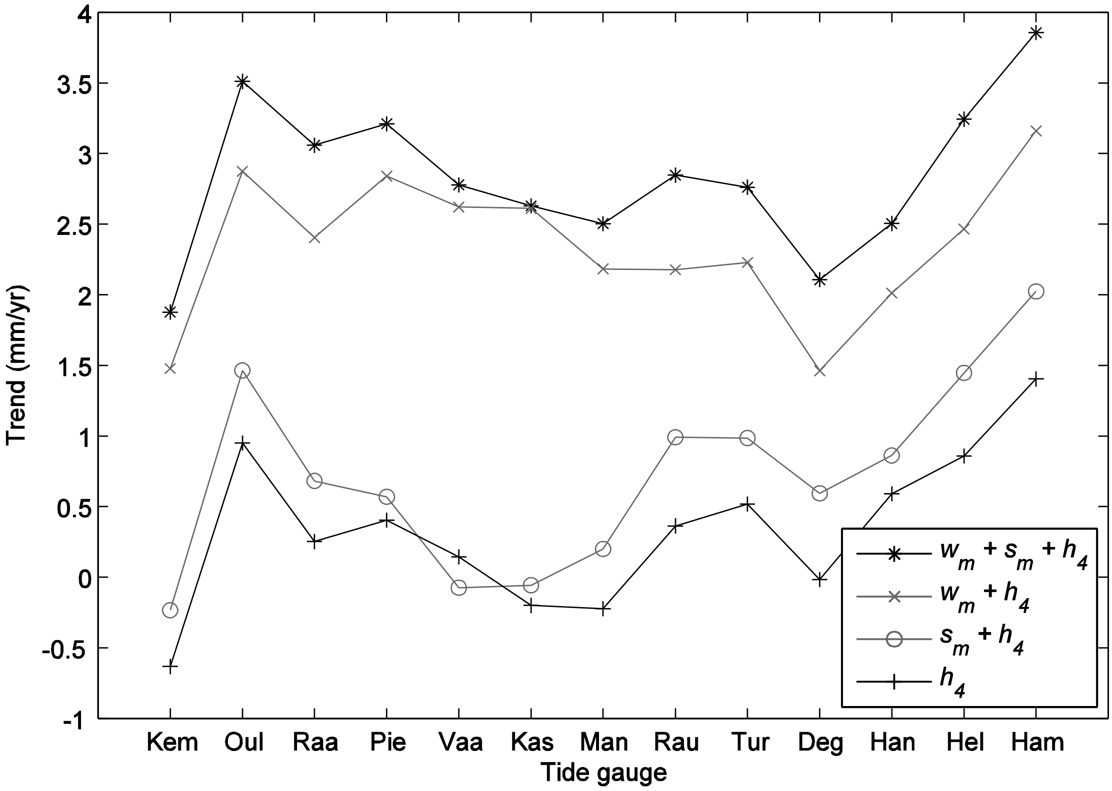



FIGURE 6.2. Trends in the annual maximum sea level anomalies $h_m + h_4 = w_m + s_m + h_4$, and different combinations of the 4-hourly anomalies $h_4$, atmosphere-related monthly anomalies $w_m$ and other monthly anomalies $s_m$, for the years 1933–2011 at the Finnish tide gauges.

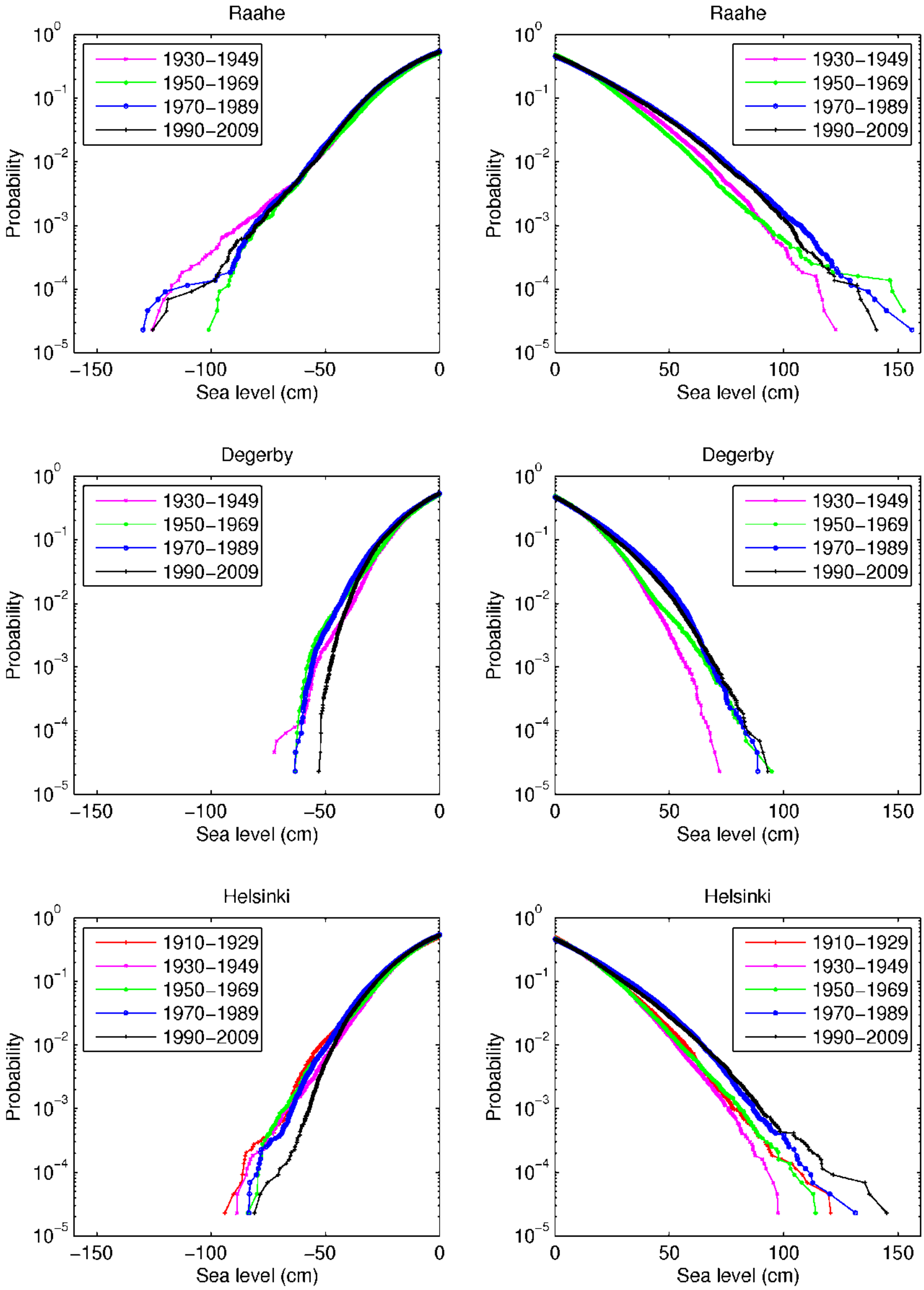



FIGURE 6.3. Probability distributions for intra-annual sea level anomalies in successive 20-year periods: cumulative distribution functions (cdf) for the low sea levels (left) and complementary cdf:s for the high sea levels (right) at Raahe (top), Degerby (middle) and Helsinki (bottom).

## 6.3 Probability distributions

To analyze the changes in sea level behaviour with a wider perspective than just the extremes, cumulative distribution functions (cdf:s) and complementary cumulative distribution functions (ccdf:s) of the intra-annual variations $h_m + h_4$ were calculated for consecutive 20-year periods (Fig. 6.3). These have changed since the early 20$^{th}$ century, as was also evident in Paper I. The apparent changes in high sea levels extend from the probability level 0.1 (sea level exceeded for approx. 37 days/year) down to extremes occurring only once in 20 years, although the scarce observations make the tails of the distributions rather uncertain. The minima show generally smaller changes than the maxima.

The ccdf:s for Helsinki for 3-month seasons (winter Jan–Mar, spring Apr–Jun, summer Jul–Sep, autumn Oct–Dec) are presented in Fig. 6.4. The largest change has occurred in winter. This also applies to the other tide gauges. The role of the atmospheric factors was again analyzed by calculating the ccdf:s for $s_m + h_4$ (Fig. 6.5, thus excluding the atmosphere-related monthly anomalies $w_m$). The apparently smaller changes in Fig. 6.5, compared to those seen in Fig. 6.4, again suggest the changes being related to atmospheric factors.

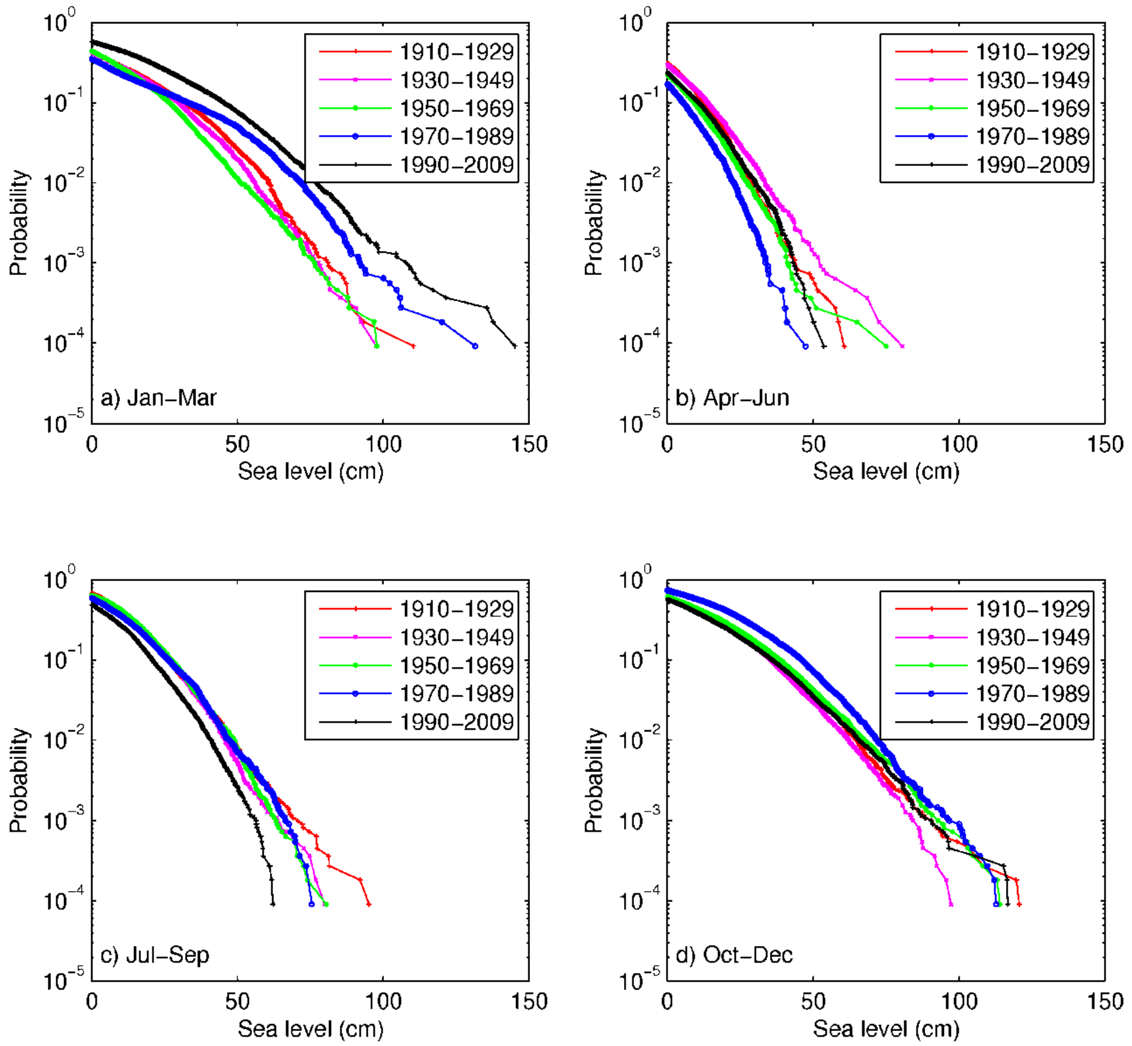



FIGURE 6.4. Ccdf:s of the intra-annual sea level anomalies ($h_m$ + $h_4$) in successive 20-year periods at Helsinki for different seasons: a) winter, b) spring, c) summer and d) autumn.

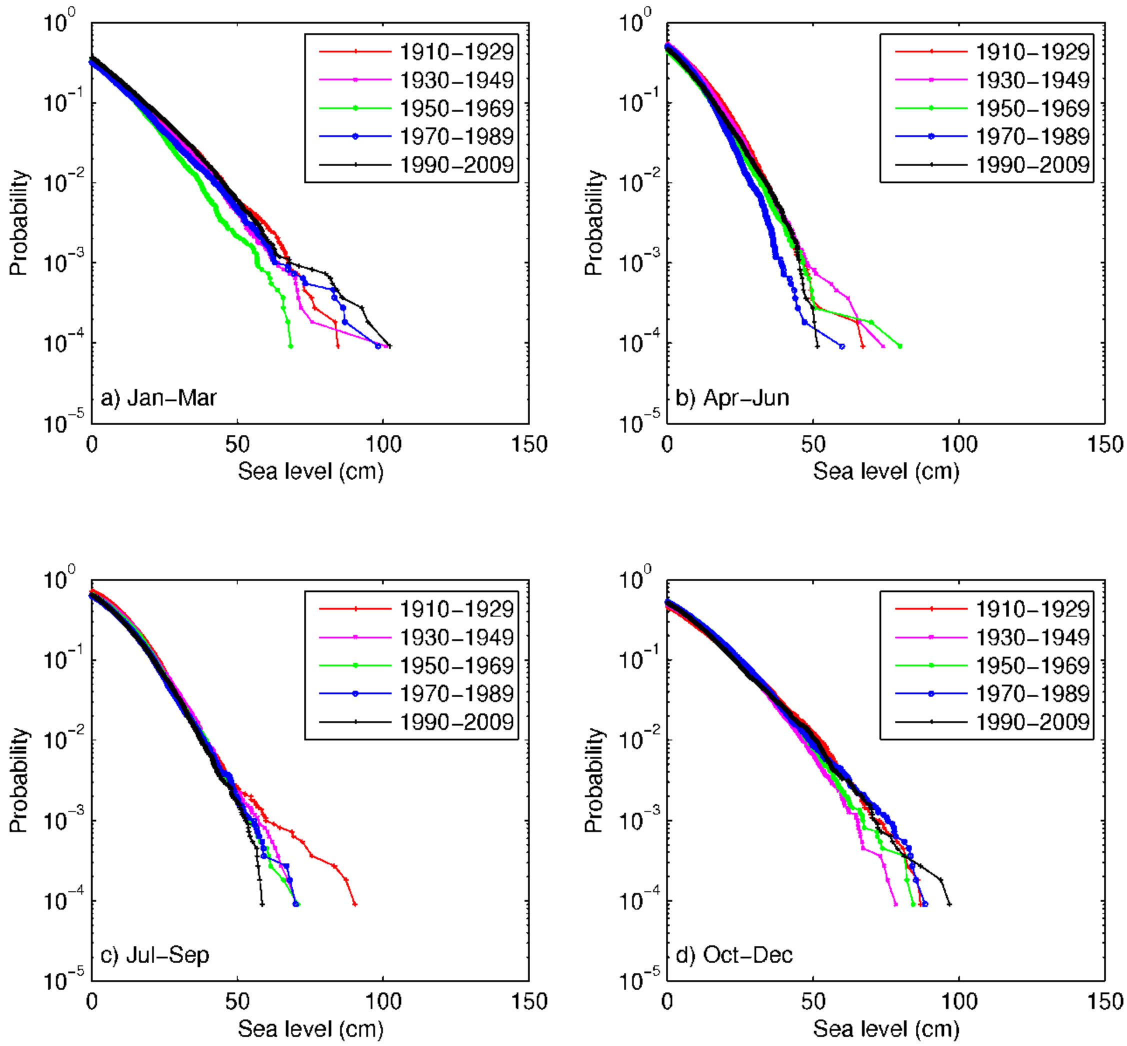



FIGURE 6.5. Ccdf:s of the intra-annual sea level anomalies excluding the atmosphere-related monthly mean variations: $s_m + h_4$, in successive 20-year periods at Helsinki for different seasons: a) winter, b) spring, c) summer and d) autumn.

To quantify the changes in the probability distribution of high sea levels, ccdf:s for the three-month seasons were calculated in consecutive 5-year periods. From these distributions, trends at four probability levels were analyzed and denoted as follows:

- extremely high: probability $5{*}10^{-4}$, exceeded approx. once in four years
- high: probability 0.01, exceeded approx. 1 day/season
- moderately high: probability 0.1, exceeded on average 9 days/season
- median: probability 0.5

Trends in sea levels corresponding to these probabilities are given in Table 6.3 for three representative tide gauges at Raahe, Degerby and Helsinki. The extremely high, high and moderately high sea levels have increased in January–March, the change being statistically significant at the 90% level. Other seasons do not show such large, uniform and significant trends. If the atmosphere-related variations $w_m$ are excluded, the remaining variations $s_m + h_4$ again show much smaller changes (Table 6.4). This further supports the interpretation that the changes seen in the January–March high sea levels are related to changes in the atmospheric factors. It should be kept in mind, however, that the linear trend analysis does not reveal changes which are not trend-like – such as an increase and a subsequent decrease.

TABLE 6.3. Average intra-annual sea level anomalies $h_m + h_4$ corresponding to certain probability levels (exceedance) at three tide gauges, and trends in these values from the early 20th century up to the present. Trends that are statistically significant at the 90% level are given in boldface.

| | | Probability | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $5*10^{-4}$ | | 0.01 | | 0.1 | | 0.5 | |
| | | Mean (cm) | Trend (mm/yr) | Mean (cm) | Trend (mm/yr) | Mean (cm) | Trend (mm/yr) | Mean (cm) | Trend (mm/yr) |
| Jan–Mar | Raahe | 109 | **3.8** | 75 | **2.2** | 38 | **2.1** | –3 | **1.2** |
| | Degerby | 69 | **4.5** | 49 | **3.3** | 30 | **2.8** | –3 | 0.8 |
| | Helsinki | 94 | **3.3** | 61 | **2.0** | 33 | **1.4** | –4 | 0.3 |
| Apr–Jun | Raahe | 51 | 0.6 | 31 | –0.7 | 11 | –0.7 | –12 | –0.3 |
| | Degerby | 34 | **–1.3** | 23 | –1.1 | 8 | –0.5 | –11 | –0.3 |
| | Helsinki | 44 | –0.7 | 27 | –0.2 | 10 | –0.3 | –11 | –0.4 |
| Jul–Sep | Raahe | 77 | 2.1 | 49 | –0.1 | 26 | –0.5 | 2 | **–0.7** |
| | Degerby | 44 | 0.0 | 35 | –0.3 | 22 | –0.5 | 4 | **–0.9** |
| | Helsinki | 67 | **–1.3** | 45 | –0.4 | 26 | **–0.7** | 4 | **–0.8** |
| Oct–Dec | Raahe | 110 | 2.0 | 77 | 1.0 | 46 | 0.6 | 10 | –0.2 |
| | Degerby | 68 | 1.0 | 52 | 0.5 | 33 | 0.6 | 8 | –0.1 |
| | Helsinki | 96 | 1.3 | 64 | 1.0 | 38 | 0.7 | 7 | 0.6 |

TABLE 6.4. Average intra-annual sea level anomalies excluding the monthly mean atmosphere-related variations, $s_m + h_4$, corresponding to certain probability levels (exceedance) at three tide gauges, and trends in these values from the early 20th century up to the present. Trends that are statistically significant at the 90% level are given in boldface.

| | | Probability | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $5*10^{-4}$ | | 0.01 | | 0.1 | | 0.5 | |
| | | Mean (cm) | Trend (mm/yr) | Mean (cm) | Trend (mm/yr) | Mean (cm) | Trend (mm/yr) | Mean (cm) | Trend (mm/yr) |
| Jan–Mar | Raahe | 82 | 0.1 | 52 | 0.3 | 21 | 0.1 | –6 | **0.3** |
| | Degerby | 50 | **1.8** | 32 | 1.2 | 12 | **0.6** | –7 | **0.3** |
| | Helsinki | 72 | 0.7 | 41 | 0.2 | 16 | 0.1 | –8 | **0.3** |
| Apr–Jun | Raahe | 56 | 1.6 | 35 | 0.1 | 18 | –0.1 | –1 | –0.2 |
| | Degerby | 37 | –0.1 | 25 | –0.2 | 13 | –0.2 | –1 | –0.2 |
| | Helsinki | 48 | –1.1 | 32 | –0.3 | 16 | **–0.4** | –0 | **–0.3** |
| Jul–Sep | Raahe | 68 | 1.6 | 42 | 0.7 | 23 | 0.1 | 3 | –0.1 |
| | Degerby | 39 | 0.2 | 29 | 0.3 | 18 | –0.1 | 5 | **–0.3** |
| | Helsinki | 61 | **–1.3** | 38 | –0.3 | 22 | **–0.3** | 5 | **–0.4** |
| Oct–Dec | Raahe | 97 | –0.1 | 63 | –0.5 | 33 | 0.1 | 3 | –0.1 |
| | Degerby | 50 | 0.4 | 36 | 0.3 | 20 | –0.1 | 1 | 0.1 |
| | Helsinki | 76 | 0.7 | 48 | 0.1 | 24 | 0.1 | 0 | **0.3** |

### 6.4 OBSERVED CHANGES IN GEOSTROPHIC WINDS

The observed changes in the intra-annual behaviour of sea levels were shown to have mostly occurred in the atmosphere-related part of the sea level variations, $w_m$. The estimate for these variations was calculated using a linear regression between the zonal geostrophic wind and sea levels. Thus, the changes should also be evident in the geostrophic winds themselves.

The seasonal cycle of the zonal geostrophic wind (Fig. 6.6) shows changes that correspond to the changes seen in sea levels (Section 6.1). There were no remarkable changes in 1910–1969. In 1970–1989, the November–December mean zonal winds were 1–2 m/s higher than before. In 1990–2009, the January–March zonal winds were about 2 m/s higher than before, both of these changes being in accordance with higher sea levels.

These changes correspond to those found by Lehmann *et al.* (2011), when studying the climate variability in the Baltic Sea area for the period 1958–2009. When analyzing changes from 1970–1987 to 1988–2007, they found a shift of strong wind events from autumn (September–October) to winter (December–February) and early spring. They also found a decrease of southwesterly winds in autumn, accompanied by an increase of easterly winds, whereas during winter, the number of westerly wind events increased, while at the same time easterly wind situations decreased.

Other studies of the climate variability in the Baltic Sea area include e.g. those of Tomingas (2002), Keevallik (2003), Keevallik and Soomere (2008) and Omstedt *et al.* (2004). The results of these show some indications of an increase in westerly winds, but no comprehensive results have been obtained. E.g., Tomingas (2002) studied the climate variability in Estonia using air pressure fields to calculate circulation indices, that essentially represented the zonal and meridional air flow. He found a statistically significant increasing trend in the zonal circulation index in winter during the period 1946–1997, and some negative trends in spring, summer and autumn. Omstedt *et al.* (2004) studied the changes in the Baltic Sea climate using 200 years of data. They found a positive trend in the frequency of anti-cyclonic circulation and westerly wind types, but a negative trend in the frequency of southwesterly wind types.

Detailed studies of the changes in wind climate itself fall outside the scope of this study, however.

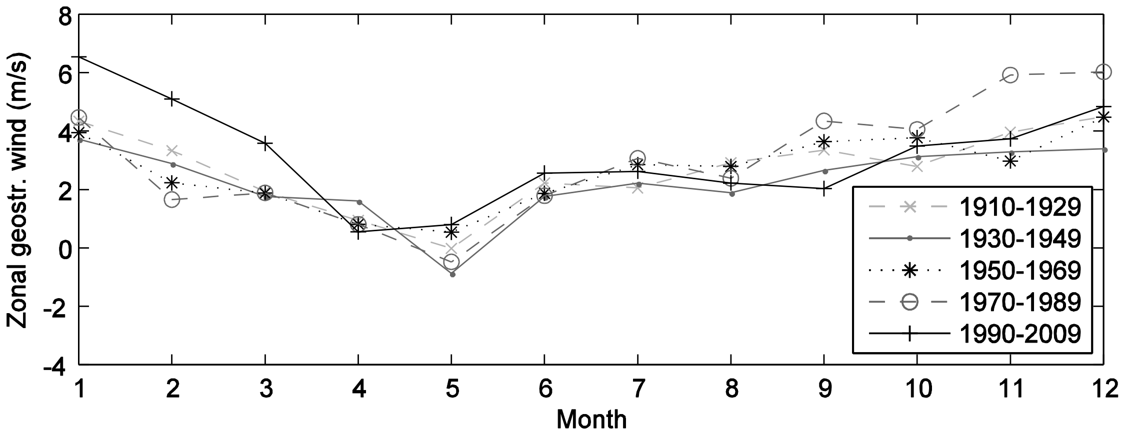



FIGURE 6.6. Monthly mean zonal geostrophic wind $U_g$ at 55°N, 15°E, in successive 20-year periods.

# 7 LONG-TERM MEAN SEA LEVEL CHANGES

## 7.1 TRENDS IN THE 20TH CENTURY

Up to the 1980s, the mean sea levels on the entire Finnish coast showed a steady declining trend, which was due to the land uplift being stronger than the sea level rise (Fig. 3.2; e.g. Lisitzin, 1964; Vermeer *et al.*, 1988; Paper II). This long-term trend was disrupted in the final decades of the 20th century, as the mean sea levels in the 1980s and 1990s were higher than the past trend would have predicted (Paper II), indicating an acceleration in the sea level trends. These high sea levels coincide with a high NAO index during these decades (Fig. 5.1), indicating stronger-than-before average westerly geostrophic flow. However, since the 1990s the NAO index has decreased, while the observed mean sea levels still remain high. This points to some other factor than atmospheric phenomena behind the change in mean sea level behaviour.

To analyze the sea level changes due to other factors than the atmospheric ones, the atmosphere-related variations $w_a$ (obtained in Section 5) were subtracted from the observed annual mean sea levels $h_a$, to yield the reduced sea level $h_r$ (Eq. 4.4, Fig. 7.1). The inter-annual variability of the reduced sea level is smaller than that of the observed annual mean sea level, because more than 80% of the observed inter-annual sea level variability is contained in the atmosphere-related variations.

The reduced time series exhibit a steady linear falling trend up to 1990s, after which the sea levels are higher than this past linear trend would predict (Figs. 7.1b and 7.1c). The linear trend up to 2000 is first analyzed in this section, and the recent acceleration is left for Section 7.2. As the trend caused by changes in the wind and air pressure conditions is excluded from the reduced sea levels, the remaining trend consists solely of the large-scale sea level rise, the land uplift, and possible trends in the other variations $s_a$. The separation of these phenomena from each other is further discussed in Section 7.3.

The linear trends calculated from the reduced time series, as well as those calculated from the observed unreduced time series, are given in Table 7.1. The trends obtained in Papers III and IV are included for comparison. In both papers, a reduction method analogous to the one used here was applied, but with different estimates for the atmosphere-related sea level variations. In Paper IV, the annual mean wind-induced component was calculated using a linear relationship between the annual mean zonal geostrophic wind and sea levels. In Paper III, a linear relationship with the NAO index was used for estimating the atmosphere-related sea level variations.

The reduction allows a more precise determination of the trend, as the uncertainties decrease from 0.2–0.4 mm/yr to 0.07–0.14 mm/yr. The reduced declining trends are 0.49–1.21 mm/yr larger than the unreduced trends, due to a rising trend in the atmosphere-related sea level variations of similar magnitude. The main reason for the difference in this trend among tide gauges is the different time spans of their data series, ranging from 1933–2000 up to 1899–2000: the atmosphere-related variations generally have larger trend in the shorter time spans. The annual mean zonal geostrophic wind has increasing trends of $8*10^{-3}$ $ms^{-1}$/yr in 1899-2000 and $2*10^{-2}$ $ms^{-1}$/yr in 1933-2000, both statistically significant at the 99% level according to Student's *t*-test. These trends are reflected in the atmosphere-related sea level trend.

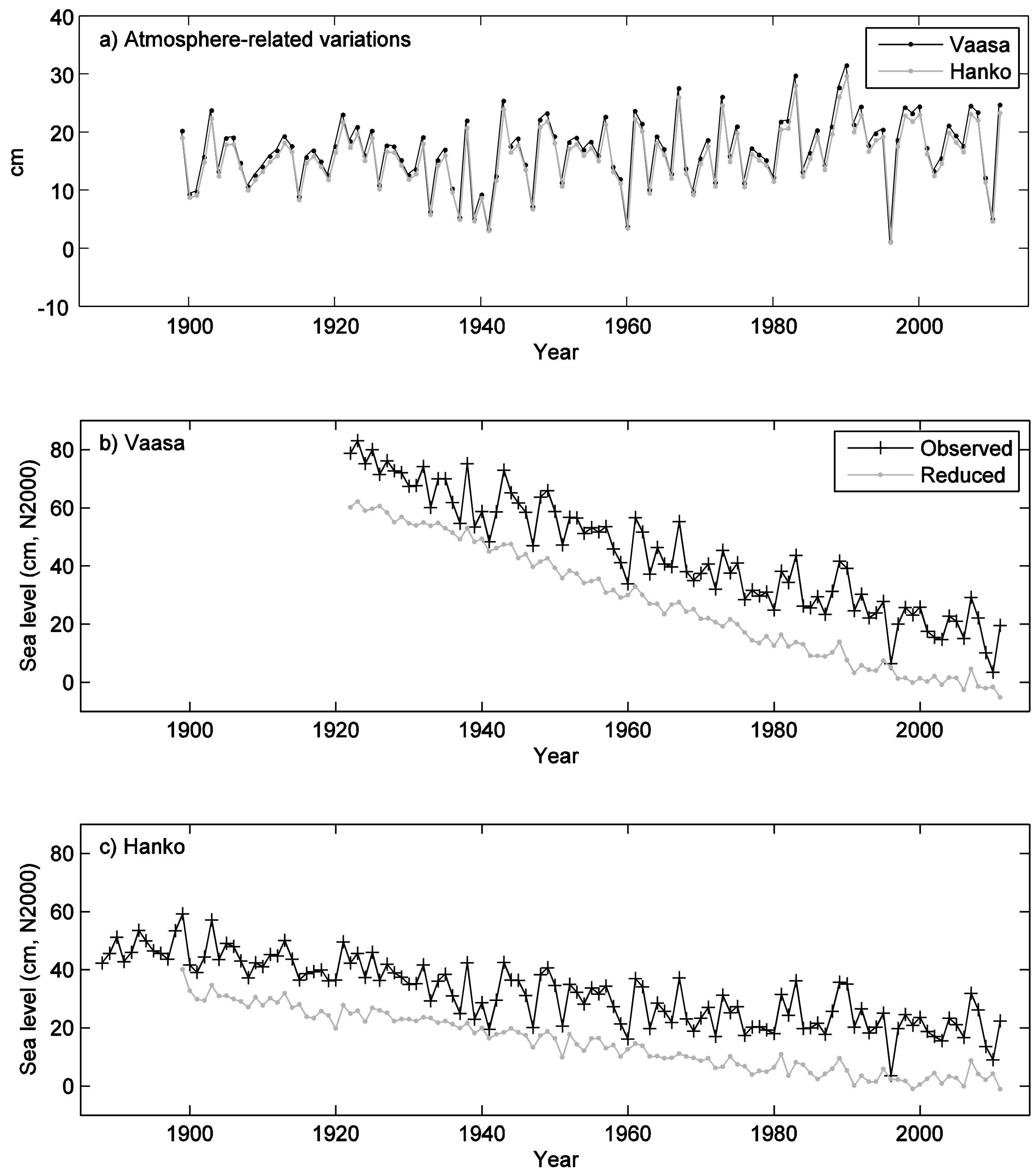



FIGURE 7.1. a) The estimate for the atmosphere-related sea level variations at Hanko and Vaasa, and the observed annual mean sea levels together with the reduced sea levels, obtained by subtracting the atmosphere-related variations from the observed annual means at b) Vaasa and c) Hanko. Hanko is the station with the longest observed sea level time series on the Finnish coast, while Vaasa has the highest land uplift rate.

TABLE 7.1. Linear trends of sea levels reduced by removing the atmosphere-related sea level variations using three different estimates: one based on the monthly mean zonal geostrophic wind ($w_a$ in this work), an estimate based on the annual mean zonal geostrophic wind (from Paper IV) and an estimate based on the NAO index (from Paper III). The trends obtained from the observed sea levels without any reduction are also given. Negative values denote declining sea levels. The uncertainties correspond to one standard deviation.

| Tide gauge | Years | Reduced by $w_a$, mm/yr | Reduced by $U_g$ (Paper IV), mm/yr | Reduced by NAO (Paper III), mm/yr[a)] | Unreduced, mm/yr |
|---|---|---|---|---|---|
| Kemi | 1923–2000 | –7.83 ± 0.14 | –7.96 ± 0.15 | –7.20 ± 0.27 | –6.90 ± 0.37 |
| Oulu | 1923–2000 | –7.49 ± 0.13 | –7.60 ± 0.14 | –6.87 ± 0.27 | –6.57 ± 0.36 |
| Raahe | 1923–2000 | –7.85 ± 0.12 | –7.96 ± 0.14 | –7.22 ± 0.26 | –6.93 ± 0.36 |
| Pietarsaari | 1922–2000 | –7.93 ± 0.11 | –8.04 ± 0.12 | –7.31 ± 0.25 | –7.08 ± 0.34 |
| Vaasa | 1922–2000 | –8.06 ± 0.09 | –8.15 ± 0.11 | –7.46 ± 0.22 | –7.23 ± 0.33 |
| Kaskinen | 1927–2000 | –7.53 ± 0.11 | –7.66 ± 0.13 | –6.99 ± 0.24 | –6.51 ± 0.37 |
| Mäntyluoto | 1925–2000 | –6.67 ± 0.10 | –6.79 ± 0.13 | –6.07 ± 0.22 | –5.72 ± 0.35 |
| Rauma | 1933–2000 | –5.81 ± 0.12 | –5.97 ± 0.15 | –5.35 ± 0.25 | –4.61 ± 0.42 |
| Turku | 1922–2000 | –4.52 ± 0.10 | –4.63 ± 0.12 | –3.94 ± 0.21 | –3.72 ± 0.33 |
| Degerby | 1924–2000 | –4.67 ± 0.10 | –4.78 ± 0.12 | –4.13 ± 0.22 | –3.80 ± 0.32 |
| Hanko | 1899–2000 | –3.21 ± 0.07 | –3.30 ± 0.08 | –2.63 ± 0.21 | –2.72 ± 0.22 |
| Helsinki | 1904–2000 | –2.57 ± 0.08 | –2.67 ± 0.09 | –2.01 ± 0.21 | –2.01 ± 0.24 |
| Hamina | 1929–2000 | –2.17 ± 0.13 | –2.35 ± 0.14 | –1.62 ± 0.26 | –0.95 ± 0.43 |

[a)] Including data up to the year 2001.

The magnitude of the longest sea level trend (0.49 mm/yr at Hanko from 1899 to 2000) is larger than the results of Ekman (1998), who estimated that the increase in southwesterly winds should have induced a sea level trend of 1–2 cm/century at Stockholm from 1825 to 1984. The difference might be due to the inclusion of the latest decades (1985–2000) in our study. The trend for the years 1899–1984 is 0.27 mm/yr at Hanko, which is in better accordance with the trend obtained by Ekman (1998).

The choice of the reduction method has an apparent effect on the results. The reduction by NAO (Paper III) has a smaller effect on the trend, as the NAO index had no significant trend during the period studied. The geostrophic wind data used in this study and Paper IV, however, contain information on local phenomena which the larger-scale NAO index cannot capture, and which have an effect on the sea levels; this is apparent considering the stronger correlation. The declining trends obtained here differ by 0.09–0.19 mm/yr from those obtained in Paper IV, even if both calculations are conceptually the same, i.e., the variations correlating with the zonal geostrophic wind have been excluded. The difference, which results from the monthly mean winds being used instead of the annual means, slightly exceeds the standard deviation of the calculated trends.

An implicit assumption made when calculating trends from the reduced time series is that the linear relationship of sea levels with the zonal geostrophic wind, which was calculated from detrended monthly mean data, also holds for long-term trends. The relationship holds for the decadal time scale (Fig. 5.3), which supports such an assumption. Also the fact that the quantitative relationship has not changed much from decade to decade (Table 5.2) is reassuring.

## 7.2 RECENT ACCELERATION

To analyze the possible acceleration in the long-term trend of sea levels since the 1990s, linear trends in overlapping 60-year periods were calculated for the observed annual means $h_a$ and the reduced annual means $h_r$ (Fig. 7.2). The trend rates of $h_a$ show an increasing tendency towards the latest 60-year periods, but the variability from period to period is large. Richter *et al.* (2011) conducted a similar analysis for the sea level data of Warnemünde, in the southern Baltic Sea, and concluded that the data do not suggest a recent unprecedented acceleration in sea level rise.

On the other hand, when calculated from the reduced sea levels on the Finnish coast, the trends show a steady increase when the latest years since 1990 are included. The trends in the period 1952–2011 were 0.6–1.5 mm/yr higher than those in 1933–1992. Trends calculated over 30-year periods show similar results, although the variability between different periods is larger. The trends in 1982–2011 were 0.8–3.3 mm/yr higher than in 1961–1990 and 1.7–3.9 mm/yr higher than in 1933–1962.

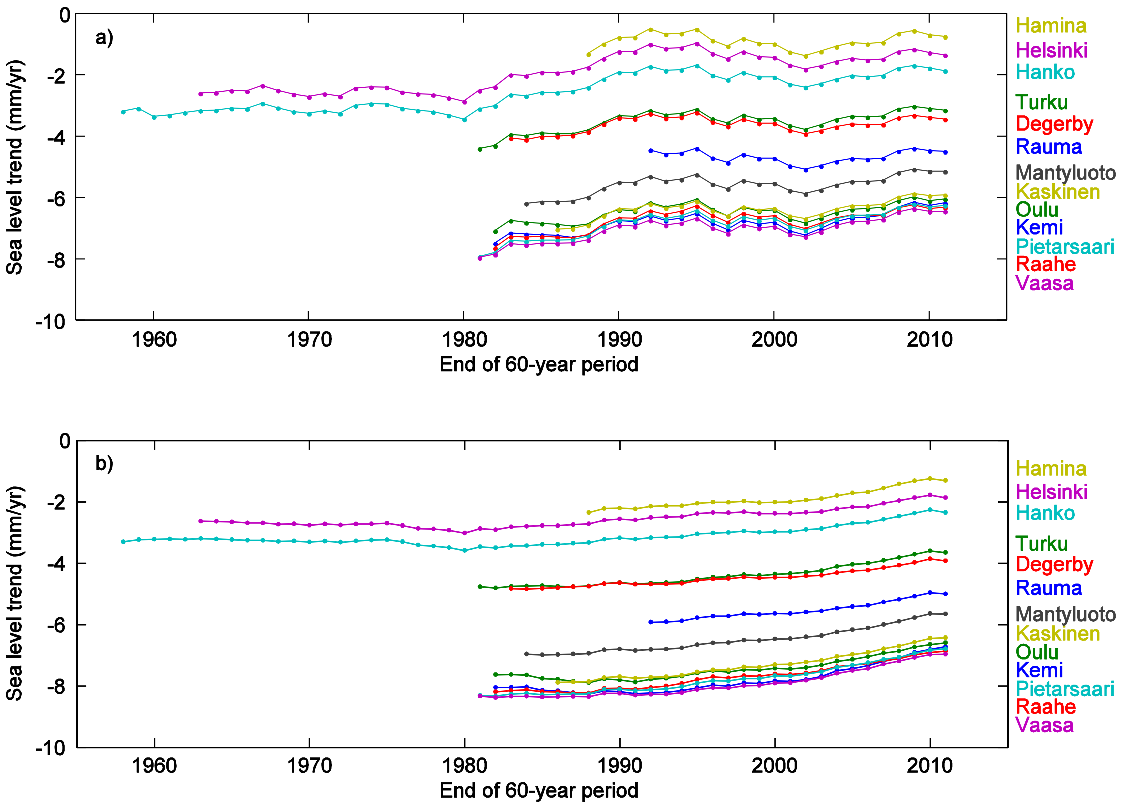



FIGURE 7.2. Linear trends in the Finnish sea level time series in overlapping 60-year periods: in a) observed sea levels and b) reduced sea levels from which the atmosphere-related variations were excluded.

The first candidate for explaining the acceleration is the large-scale sea level rise due to a warming climate. The global mean sea level has been rising faster during the last two decades than before. The rate in 1993–2009 was 3.2 ± 0.4 mm/yr, which was 1.5 mm/yr higher than the average rate of 1.7 ± 0.2 mm/yr in 1900–2009 (Church and White, 2011). Calculated from the longest Finnish sea level time series at Hanko (Helsinki), the rate in 1993–2009 was 1.1 ± 1.2 (1.2 ± 1.2) mm/yr, and in 1900–2009 (1904–2009), –2.98 ± 0.07 (–2.40 ± 0.07) mm/yr. The difference between these is 4.0 (3.6) mm/yr, three times larger than the uncertainty (one standard deviation) of the former trend; the rate in 1993–2009 is thus significantly different from the long-term average rate. This suggests a stronger regional acceleration than seen in the global averages. However, a time series of 17 years is still quite short for a reliable determination of numerical values for the acceleration, due to the large year-to-year variability of $h_r$.

As pointed out in Section 5.2, the correlation between the detrended annual mean sea levels and the geostrophic winds degrades slightly when the latest decade of data – 2001–2011 – is included, compared to calculating the correlation up to 2000 only. This might be related to the non-linear behaviour of the reduced sea level during the latest decade. This non-linearity means that some of the variations unrelated to atmospheric factors are not removed by linear detrending, but enter as noise into the correlation calculations.

The possible acceleration in the long-term trends of the Baltic sea levels has been analyzed in several studies. Generally, no reduction for the atmosphere-related effects was done, so these studies also reflect the effect of the atmosphere-related high sea levels in the 1980s and 1990s.

Ekman (1999, 2010) studied the 200-year-long sea level time series from Stockholm, and found that the long-term trend in 1885–1984 was 1.0 ± 0.3 mm/yr larger than the trend in 1774–1884. He concludes that this acceleration is related to an increase in the general climatic sea level rise, and is not dependent on any specific conditions in the Baltic Sea. Such an acceleration is not comparable with this study, as this study has concentrated on sea levels from the early 20$^{th}$ century onwards only, and thus the acceleration from the 19$^{th}$ century to the 20$^{th}$ century is not included here.

Dailidienė *et al.* (2006) studied the long-term trend in sea levels at Klaipėda Strait in 1898–2002. They found a slight and statistically insignificant trend until the 1940s, but a more pronounced rise during the latter half of the 20$^{th}$ century. Since the 1970s, the sea level has risen by about 3 mm/yr on the Lithuanian coast, while the rate of sea level rise during 1898–2002 was 1.3 mm/yr. They also found the sea level rise as being more intensive during the cold period of the year than during the warm period, and related this rise to changes in the atmospheric conditions. This is in accordance with the results of this study concerning the change in the sea level trends on the Finnish coast in the 1980s and 1990s, related to atmospheric factors.

Stramska and Chudziak (2013) analysed satellite altimetry data of the Baltic sea level and found a rising sea level trend of 3.3 mm/yr in 1992–2012, similar to the globally-averaged sea level trend of 3.1 mm/yr during that period. They also examined the temporal variability of the trend, but noted that the detection of decadal changes in the sea level trend is a very challenging undertaking, owing to the substantial variability in sea levels in the Baltic Sea, for example due to meteorological forcing, and the relatively short data records.

Suursaar and Kullas (2009) analysed the sea level trends on the Estonian coast in the 20$^{th}$ century, and found an upward mean sea level trend of 1.5–2.7 mm/yr, after taking into account the land uplift. The rates were roughly equal to or insignificantly higher than the global mean sea level rise estimate of 1.7 mm/yr. The highest rate – 2.7 mm/yr – observed at Pärnu was explained by a change in wind conditions (Suursaar and Kullas, 2006).

Navrotskaya and Chubarenko (2013) studied sea level trends in the lagoons of the southeastern Baltic. They found a positive sea level trend of 1.7–1.9 mm/yr over the last 100–150 years, while the second half of the 20th century (1959–2006) showed an increased sea level rise of up to 3.6–3.7 mm/yr in the Vistula Lagoon, and 2.3 mm/yr on the sea coast of the Baltic Sea.

### 7.3 Separating the large-scale sea level rise and land uplift

Assuming that the other sources of variations comprising $s_a$ have a negligible trend, the trends in the reduced sea levels (Eq. 4.4) consist mainly of the large-scale sea level trend, originating from outside the Baltic Sea, and the land uplift. In principle, two approaches are possible for separating these components from each other. In the past, it was customary to choose an estimate for the large-scale sea level rise, and subtract it from the observed sea level change to obtain the land uplift rate. In Paper III, a large-scale sea level rise of 1.5 mm/yr (global average; Church *et al.*, 2001) was used, and in Paper IV, 1.7 mm/yr (global average; Bindoff *et al.*, 2007). Lisitzin (1964) suggested a value of 1.0–1.1 mm/yr for the sea level rise and Ekman (1996) a value of 1.2 mm/yr for the sea level rise and 0.6 mm/yr for the rise of the geoid. Due to the large uncertainty in these values, compared to the fairly precise determination of the observed sea level trend, the trends in apparent sea level, i.e., the sea level change in relation to the bedrock, instead of the absolute land uplift rates, were primarily presented in some studies (Lisitzin, 1964; Vermeer *et al.*, 1988). The apparent land uplift rate or sea level change is also a value having a practical significance. It is the rate that determines how much land is gained from the retreating sea, or how the height of a certain construction changes in relation to the sea level, which in turn determines the flood risk, for instance.

Recent GPS-based observations on the crustal movements in Finland allow an opposite approach. From such data, the land uplift rates can be determined independent of the sea level observations (e.g. Lidberg *et al.*, 2007; Vestøl, 2006). Combining these rates with the observed sea level rates results in a determination of the rate of the large-scale sea level rise and its variation from place to place. Such local rates are of interest, as the uneven geographical distribution of the past large-scale sea level rise is still not known very well, with the exception of the most recent decades, for which world-wide satellite data exist. This approach, which requires a thorough analysis of the GPS data, is not further pursued in this study.

The observed acceleration of sea level trends during recent decades might also depend on location. Analyses of changes in local sea level trends – such as Section 7.2 – might provide valuable information for studies of the geographical distribution of sea level rise caused by the melting of land-based ice masses or ocean density and circulation changes. Before conclusions on such matters can be drawn, however, it is necessary to consider other possible factors that might contribute to the observed acceleration, e.g., changes in the land uplift rates, or a trend in the other variations $s_a$, like changes in Baltic Sea salinity.

### 7.4 Future mean sea level scenarios

Mean sea level scenarios for the Finnish coast up to 2100 were constructed in Papers III and IV. The results of Paper IV are summarized here, as they were based on the most recent knowledge and were an update to Paper III. The mean sea level scenarios were constructed as a combination of three factors: the large-scale sea level rise, land uplift, and atmosphere-related changes.

An elaborate analysis of the large-scale sea level rise, which mainly originates from changes in ocean density and circulation as well as the melting of ice sheets, glaciers and ice caps, was presented in Paper IV. Several recently-published projections for the global mean sea level rise, based on different methods as well as assumptions on the climate change, were assessed: Meehl *et al.* (2007), Katsman *et al.* (2008, 2011), Pfeffer *et al.* (2008), Jevrejeva *et al.* (2010, 2012), Grinsted *et al.* (2010), Vermeer and Rahmstorf (2009), Horton *et al.* (2008) and Rahmstorf (2007). The projections ranged from 20 cm up to 200 cm of sea level rise by the end of this century (see Table 4 of Paper IV). These projections were combined to obtain a probability range for the sea level rise, resulting in a 5% to 95% range for the global average sea level rise from 2000 to 2100 being 26–155 cm. The uncertainty range of several tens of centimetres mainly results from the uncertainty in the fate of the West Antarctic and Greenland ice sheets in a warming climate.

The large-scale sea level rise is not evenly distributed geographically. This is revealed by recent satellite observations (Cazenave and Llovel, 2010). In the future, the uneven distribution of melt waters from glaciers due to the gravitational effect of the large ice masses (Mitrovica *et al.*, 2001) might further add to the uneven distribution of sea level rise, especially in the case of the highest projections, which contain a significant contribution from the Greenland and West Antarctic ice sheets. The sea level rise contribution from the melting of the Greenland ice sheet and the smaller glaciers and ice caps will be smaller on the Finnish coast than globally, while the contribution from the West Antarctic ice sheet will be slightly larger due to the gravitational effect. The ocean density and circulation changes are projected to result in a slightly larger sea level rise on the Finnish coast than globally. Altogether, the large-scale sea level rise was estimated to have a smaller effect on the Finnish coast than globally – the 5% to 95% probability range extending from 24 to 126 cm.

Land uplift contributes from –40 to –100 cm in a century to the apparent sea level change observed on the Finnish coast (Table 3 of Paper IV), while changes in atmospheric factors were projected to add on average 6–7 cm to the sea level up to 2100, with an uncertainty ranging from a 4 cm decline to a 19 cm rise (Table 7 of Paper IV). This estimate was based on extending the past linear relationship between the annual mean zonal geostrophic wind and sea level into the future, which was considered appropriate, as the relationship has not changed much in the past (as in Table 5.2). Scenarios for the geostrophic wind were obtained from nine global circulation models, selected from those used in the 4$^{th}$ Assessment Report (AR4) of the IPCC (Gregow *et al.*, 2011; Meehl *et al.*, 2007).

The differing land uplift rates result in varying sea level scenarios along the Finnish coastline; the contribution of the other factors to the spatial differences is smaller. A sea level rise of approximately +30 cm was projected for the Gulf of Finland, with an uncertainty ranging from –20 cm to +90 cm. For the Bothnian Sea, the scenarios range from –70 to +70 cm and for the Bothnian Bay, where the land uplift is strongest, from –70 to +30 cm, the average scenario predicting a decline in the sea level in these areas (Table 8 of Paper IV). The uncertainty ranges mainly reflect the wide range of the large-scale sea level rise scenarios.

# 8 CONCLUSIONS

The main conclusions of this work, to fulfill the objectives given in Section 1, are:

1) Variations in the atmospheric factors – air pressure and geostrophic wind – explain 82–88% of the year-to-year variability of annual mean sea levels and 76–81% of the intra-annual variability of monthly mean sea levels on the Finnish coast. This is revealed by a correlation between the monthly mean sea levels and the monthly mean zonal geostrophic wind over the Baltic Sea. The correlation has a time lag: the sea levels correlate with the same month's as well as previous month's zonal geostrophic wind. This is due to the mechanisms behind the correlation: firstly, wind and air pressure affect sea levels by changing the total water volume of the Baltic Sea, which responds with a delay due to the limited water transport capacity of the Danish Straits, and secondly, redistribution of water occurs inside the Baltic Sea basin, which responds in less than a couple of days.
2) The seasonal sea level variability on the Finnish coast has changed during the past century. In 1970–1989, sea levels were higher than previously in November–December. In 1990–2009, sea levels were higher than previously in January–March. The annual sea level maxima on the Finnish coast have increased by 15–30 cm from the 1930s up to the present. The probability distributions of intra-annual sea level variability have changed since the early 20$^{th}$ century: high sea levels with occurrences ranging from some weeks/year to less than once a year show an increase. The increase is most pronounced in the winter (Jan–Mar) period.
3) The changes in seasonal sea level variability are related to changes in atmospheric factors, as they correspond to changes in the monthly mean zonal geostrophic wind over the Baltic Sea. The observed statistically significant changes in sea level maxima and probability distributions are also related to changes in the monthly mean zonal geostrophic wind conditions. There are also changes not related to these, but they are generally not statistically significant.
4) The relative mean sea level on the Finnish coast has been declining at a rate of 1.0–7.2 mm/yr during the 20$^{th}$ century, due to land uplift being stronger than the large-scale sea level rise. The long-term declining trend has slowed since the 1980s. The prevailing westerly winds and resulting high total water amount in the Baltic Sea contributed to this in the 1980s and 1990s, but the slowing of the declining trend since 1990s is no longer related to local atmospheric factors. The changes in the sea level trends are larger than the changes observed in the global mean sea level rise during the most recent decades, but the time series are still too short for the drawing of firm conclusions.
5) On the Finnish coast of the Gulf of Finland, the mean sea level is projected to rise in the future, in contrast to the past declining trend. This is mainly due to the accelerating large-scale sea level rise, originating from outside the Baltic Sea, the rate of which is projected to exceed the rate of the land uplift. On the Finnish coast of the Gulf of Bothnia, on the other hand, especially its northern part, the average scenario projects that land uplift will still balance the sea level rise in the future. The uncertainties are large, however, and the high-end scenarios project rising mean sea levels everywhere on the Finnish coast.

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